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Assessment of the Critical Populations at Risk Due to Radiation Exposure in Structures

Georgia Inst. of Tech., Atlanta

Prepared for

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Bernard Kahn, Geoffrey G. Eichholz, and Frank J. Clarke.

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In preparation for a survey of radiation doses in U.S. structures, information on survey criteria, techniques, and results was reviewed and evaluated, some survey procedures and calculational methods were developed and tested, and a protocol for a nationwide survey was prepared. Measures to prevent or remedy significantly elevated doses from building materials were reviewed from the viewpoint of cost-effectiveness, application of several measures was recommended under specific conditions, and a selected method was tested. In the U.S., building materials may contain elevated levels of radionuclides if they contain shale, granite, and pumice among naturally occurring materials, and phosphate slag, phosphogypsum, and fly ash among industrial byproducts. Some additional materials have been identified in other countries. The highest gamma radiation exposure rates found in U.S. structures due to building materials are attributed to concrete that contains phosphate slag from the thermal process for phosphorus production.

KEYWORDS: *Irradiation, *Structures, *Radiation dosage.

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Abstract

In preparation for a survey of radiation doses in U.S. structures, information on survey criteria, techniques, and results was reviewed and evaluated, some survey procedures and calculational methods were developed and tested, and a protocol for a nationwide survey was prepared. Measures to prevent or remedy significantly elevated doses from building materials were reviewed from the viewpoint of cost-effectiveness, application of several measures was recommended under specific conditions, and a selected method was tested.

In the U.S., building materials may contain elevated levels of radionuclides if they contain shale, granite, and pumice among naturally occurring materials, and phosphate slag, phosphogypsum, and fly ash among industrial byproducts. Some additional materials have been identified in other countries. The highest gamma radiation exposure rates found in U.S. structures due to building materials are attributed to concrete that contains phosphate slag from the thermal process for phosphorus production. Elevated Rn-222 daughter concentrations (WL values) have been measured in some structures built with this material, but WL values in building air are so responsive to ventilation rates and inflow of Rn-222 from the outside that building material could not be identified unequivocally as the major source.

An increase in the ventilation rate is recommended as the most cost-effective measure for reducing elevated Rn-222 daughter concentrations in the air of poorly ventilated buildings. At least one type of wall coating has been found to be impermeable to radon and appears to be cost-effective if it can be maintained without penetrations for reasonable periods.

The protocol presents a 3-year program of regional or statewide surveys, unified through common guidelines, intercalibration, quality assurance, and data compilation. The surveys are designed to determine the radiation dose potential of building materials, the pattern of gamma radiation and WL background, average values of the elevation of gamma radiation exposure rates and WL values in structures, and the sources and extent of significantly elevated radiation doses in structures from building materials.

Procedures were developed in the study for determining the radiation dose potential of building materials in terms of a radiation exposure index and for predicting exposure rates in structures from the index with a calculational model. A procedure is also recommended for performing Ra-226 measurements to identify structures that have potentially elevated WL values due to building materials, in order to distinguish among various sources of the Rn-222 in building air and reduce the number of needed WL measurements.

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ASSESSMENT OF THE CRITICAL POPULATIONS AT RISK DUE TO RADIATION EXPOSURE IN STRUCTURES

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1. Introduction

Emission and attenuation of radiation by building materials significantly affect the dose to which persons are exposed. The magnitude of this dose from materials needs to be assessed to obtain the value of the normal radiation background dose and also to prevent or remedy unacceptably high doses. This report identifies the building materials that are major contributors to the radiation exposure on the basis of available information, recommends field study procedures to determine exposure levels from these materials, and examines the cost-benefit balance of remedial measures.

The building materials that contribute noticeably to radiation exposures contain the naturally occurring terrestrial radionuclides. Human exposure is principally to the whole body from external gamma rays and to the lungs from internal alpha particles. The gamma rays are emitted by the U-238 decay chain, the Th-232 decay chain, and K-40. The main alpha-particle emitters are the short-lived progeny of Rn-222, the daughter of Ra-226 in the U-238 decay chain. Radon-222 is a gas that emanates (is exhaled) from soil and rock in the ground as well as building materials, and decays to form particulate radionuclides that can deposit in the lungs. Cosmic rays -- expecially muons -- also contribute to the external exposure. To a much lesser degree under usual conditions, radiation exposure is also due to other radiations from the cited terrestrial radionuclides, other naturally occurring radionuclides, and man-made radionuclides such as fallout from atmospheric nuclear tests.

The value of the radiation dose to persons from structural materials is a complex function of the concentration of radionuclides in the materials, the form of the materials and their distribution within the structure, building construction and use, and the extent of occupancy. Materials in walls and floors emit gamma rays and simultaneously attenuate gamma rays from the ground, air, and other structures outside. Roof and ceilings slightly reduce the muon flux. Radon enters buildings from the ground and air outside and from materials within. The concentrations of Rn-222 daughters in building air depend on the amount of Ra-226 in these sources, the degree to which Rn-222 can reach building air, and the rate at which the daughters are removed by ventilation, filtration, deposition and radioactive decay. The dose from Rn-222 daughters in human lungs is controlled by inhalation and retention rates and the distribution of deposited particles.

This complexity suggests that a detailed nationwide survey will be necessary to assure that those structures are found in which building materials cause significantly elevated radiation doses to occupants and to check the population dose increments that have been estimated for structures in the United States. In preparation for such a survey, similar efforts in other countries or on a smaller scale were reviewed, and data on measured radionuclide concentrations and exposure rates associated with building materials were compiled. Also considered were needs for major supporting activities, especially determining long-term average radiation backgrounds at least as accurately as the radiation levels in structures; developing mathematical models for computing doses to persons from the relatively few measurements performed in the survey; and establishing criteria for characterizing radiation levels as significantly elevated, based in part on cost-benefit relations for remedial measures.

Nationwide surveys of population radiation exposures that are under way or have recently been completed in several other countries provide guidance for procedures and instrumentation that can be applied in the Unites States. These surveys have shown that gamma radiation exposure rates are generally somewhat below outside levels in buildings constructed with wood or composition materials, and somewhat above outside levels in brick, concrete, and stone buildings. Radon-222 concentrations were on the average somewhat higher inside than outside, but these data are fewer than gamma-ray exposure measurements and probably less representative because Rn-222 concentrations are so variable. Some building materials that contain relatively high radionuclide concentrations were identified as possible sources of higher gamma-ray and Rn-222 levels.

In the U.S., two detailed surveys of elevated radiation exposures in structures have demonstrated effective procedures and indicated some of the difficulties in data interpretation, although both applied to radiation sources beneath houses rather than in building material. The first survey investigated radiation levels from uranium-mill tailings used mainly as fill beneath and around houses near the tailings piles in the western U.S., especially at Grand Junction, Colorado. The second examined houses built on phosphate-mineral land -- mostly areas reclaimed after phosphate mining -- in Florida, especially in Polk and Hillsboro counties. The concentration of Ra-226 is usually several hundred picocuries per gram (pCi/g) in uranium-mill tailings and of the order of 10 pCi/g in phosphate-mining backfill, compared to usual concentrations in soil near 1 pCi/g. In both situations, the main radiation problem is Rn-222 seeping into houses through foundations and walls, although gamma radiation was also significantly elevated in many instances at Grand Junction. The relation of dose rates to radiation source strength and the application of remedial measures would be different from these situations where the radiation source is structural material in the building itself, the topic addressed in this report.

A number of local surveys and studies of radiation exposures in buildings and radioactive building materials in the U.S. have provided information consistent with that in other countries. The only material used in structures that so far has been found to contain clearly elevated levels of terrestrial radionuclides is concrete manufactured with slag from the thermal process for phosphorus production. Some other materials that may contain elevated radionuclide concentrations have not caused unduly high gamma radiation and Rn-222 levels in houses, although far too few structures have been examined to assure that these findings apply nationally.

Calculational methods to guide survey programs by relating measured radionuclide levels in materials and measured radiation levels in sample structures to doses to persons in a variety of structures are still in their early stages. Population averages of incremental doses due to structures have been estimated by applying empirically derived factors for certain building material categories to gamma-ray exposure rates measured outside. Upper limits of gamma-ray exposure rates have been related to terrestrial radionuclide concentrations in wall and floor materials by assuming that the structure is an infinitely thick radioactive sphere. Equilibrium Rn-222 concentrations in building air have been computed from the Ra-226 content and estimated Rn-222 exhalation rates of walls and floors, the turnover rate of air within the building, and the radioactive decay of Rn-222 in air. Attempts to infer Rn-222 concentrations in building air from gamma-ray exposure rates measured for houses built on uranium-mill tailings and phosphate lands have been notably unsuccessful except as order-of-magnitude indications.

The recommendations by the Surgeon General of the U.S. Public Health Service for remedial action where uranium-mill tailings were used in or beneath dwellings have been applied as radiation protection criteria. Because these recommendations were based in part on cost-benefit evaluations of the conditions under consideration, different criteria may be considered where other remedial actions are possible or necessary. Such differences are reflected in the limiting values for preventive measures instituted by the U.S. Environmental Protection Agency (EPA) in its proposed rules for the use in building products of wastes derived from phosphate and uranium mining.

Determination of the dose rate added or subtracted by building materials to the environmental radiation background dose requires a knowledge of ambient gamma-ray exposure rates and Rn-222 daughter concentrations. A general pattern of gamma-ray exposure rates in the U.S. has been recognized and instruments for measuring these values are readily available. Much less is known about Rn-222 daughter concentrations because they fluctuate greatly and measurements are less simple. Determining the increment due to building materials is especially difficult where it tends to be obscured by fluctuating levels both inside and outside.

In this report, the available information concerning observed gamma-ray exposure rates and Rn-222 daughter concentrations in structures and elevated radionuclide concentrations in building materials is summarized to identify structure types and building materials that could be major contributors to the radiation dose of occupants. Situations that could result consistently in significantly elevated doses are evaluated. A test survey is described that was undertaken to develop a methodology for relating the radiation exposure potential of building materials due to their radionuclide content to gamma-ray exposure rates and Rn-222 concentrations within various structures. The radiation exposure potentials of typical materials determined in the test survey are reported to indicate the range of normal radiation doses that may be encountered, and present some examples of elevated radiation exposure rates and Rn-222 levels. A field study was designed to determine the range of dose increments due to gamma rays and Rn-222 daughters from building materials and to find structures that cause significantly elevated doses. A procedure is given for determining the cost-effectiveness of control technology in existing and new structures, results of measurements are reported of what is believed to be the most appropriate control technology for Rn-222 daughters, and the various recognized remedial and preventive measures are discussed with regard to applicability under various conditions.

2. Reported Sources and Levels of Radiation Exposure in Structures

2.1 Radiation Protection and Measurement Criteria

The radiation protection criteria applied to building materials and the major sources of uncertainty in relating measured values to these criteria need to be considered at the outset to guide data collection and evaluation. Criteria are not available at this time for building materials as a category, but in their absence useful guidance is provided by criteria established for remedial action at buildings constructed on or with uranium-mill tailings and by proposed regulations for building products manufactured from phosphate and uranium mining wastes. Temporal and spatial variations in radon concentrations and gamma radiation levels appear to be the most important causes of uncertainty in determining dose increments on an annual basis for specific structures. Apportioning measured values between sources in building materials and the ground is particularly difficult where the radiations from the two sources are indistinguishable and of the same magnitude.

Environmental criteria for radiation exposure to the whole body from gamma rays are given in units of microroentgen per hour (μR/hr) and those for radiation exposure to the lungs from alpha particles emitted by radon daughters are in units of working level (WL). The WL unit is defined as any combination of short-lived radon daughter products in 1 liter of air that will result ultimately in the emission of 1.3×10^5 million electron volts (MeV) of alpha-particle energy. The concentration of Rn-222 with which the short-lived daughters that result in 1 WL are in equilibrium is 100 pCi/l, but the daughters are usually not in equilibrium with Rn-222 or each other in air, either outside or in normally ventilated structures.

The criterion for whole-body doses was derived from the radiation protection guide of 500 millirem per year (mrem/yr) above ambient levels to the whole body of individuals in the general population recommended by the Federal Radiation Council. The WL criterion was taken to be approximately one-tenth of the occupational exposure limit (St70). The relation to 500 mrem/yr involves the conversion factor from measured value to rem, considerations of the balance of cost, benefit, and risk, and adjustment for the fractional time period of personal exposure ("occupancy factor"). Various values between 0.5 and 0.8 have been used to relate the exposure rate to the depth tissue dose from the mixture of gamma rays in terrestrial background radiation (UN77). Recently, 0.58 rem/R has been suggested as the conversion factor from energy-averaged environmental gamma radiation to organ-weighted somatic dose (OB78). The conversion factor from WL units is much more uncertain because of the assumptions that must be made concerning the form and relative amounts of Rn-222 daughters, the fractions deposited, and the tissue distribution of deposited particles. A factor of 4.3 rad/yr per WL has been derived for conditions in uranium mines (Ha72); UNSCEAR has recommended a factor of 9 μrad/hr per pCi/l for the mean dose to the lungs from Rn-222 outdoors and in houses, which corresponds to 7.8 rad/yr per WL (UN77). The ratio of rem to rad for alpha-particle radiation in lungs has been taken as 10 (NC75).

The Surgeon General has recommended the following remedial action levels above the outside background levels for dwellings constructed with or on uranium-mill tailings (St70):

External gamma radiation	Radon daughter products	Remedial action
above 100 μR/hr	above 0.05 WL	is indicated
from 50 μR/hr	from 0.01 WL	may be suggested

More recently, the U.S. Energy Research and Development Administration in 10 CFR Part 712 has applied these levels of 50 μR/hr and 0.01 WL as criteria for determining the possible need for remedial action in dwellings. These values correspond to average dose equivalent rates to the total body and lungs of 250 and 780 mrem/yr, respectively, during continuous occupancy when the factors given above are used. The agency has applied the same levels to school rooms, presumably balancing the lower occupancy factor against the suitability of a lesser value where children are exposed. Criteria of 150 μR/hr and 0.03 WL were applied to all other structures in consideration of briefer occupancy. The limit above background set by the U.S. Nuclear Regulatory Commission in 10 CFR Part 20 for individuals not occupationally exposed at any location, inside or outside, is 0.03 WL.

The EPA has proposed rules under the Resources Conservation and Recovery Act of 1976 (PL 94-580) that prohibit building products manufactured from waste derived from phosphate rock mining, phosphoric acid and phosphorus production, and uranium mining if these exceed background levels by 5 μR-/hr or 0.03 WL. Use of land reclaimed with these wastes is also prohibited if the exposure rates or radon-daughter concentrations are at or above these levels (EP78).

A major cause of uncertainty in determining radiation doses from structures and identifying structures that cause excessive dose rates is the fluctuation at specific locations and the variation among locations of the background value that must be subtracted from the value measured within a structure. These fluctuations and variations have been found to exceed 5 μR/hr and 0.01 WL, the lowest criteria cited above, at some measurement sites in the United States. Where such variability significantly affects the results, gamma radiation exposure rates or WL values must be measured simultaneously outside and inside structures, and the outside locations must be appropriate for defining the background within these structures.

Concentrations of ambient Rn-222 and its daughters, especially, vary over large ranges in brief intervals. Year-long measurements of Rn-222 concentrations in outside air at a rural location in New Jersey for 3-hour periods showed a log-normal distribution with a log-mean value of 0.17 pCi/l, a geometric standard deviation of $\overset{\times}{\div}1.8$, and a range from 0.03 to 1.4 pCi/l (Ha78b). Measurements of Rn-222 daughters in outside air at an urban location in Ohio during early morning for eight years yielded a log-mean annual value corresponding to 0.004 WL with a geometric standard deviation of $\overset{\times}{\div}1.4$ for annual averages, and a range of daily values within one year from 0.0004 to 0.015 WL (Go64, Co70). Measurements of Rn-222 daughters summarized in Section 2.4 for structures built with materials that do not contain elevated Ra-226 concentrations show mean values between 0.002 and 0.007 WL, log-normal distributions, and similarly wide ranges.

The average daily terrestrial exposure rate at the same location in New Jersey for a 22-month period was 9.0 μR/hr, but ranged from 4.5 to 11.5 μR/hr; an additional 3.9 μR/hr is attributed to cosmic rays (Mi78). The lowest exposure rates occurred in winter and were probably due to snow cover. Even measurements within dwellings averaged over numerous locations were higher by 1 μR/hr in summer than in winter (Li73, Ni78). The extent of differences in the terrestrial exposure rate from place to place is indicated in the summary by Oakley (Oa72) of ground-level gamma radiation exposure rates determined by the Airborne Radiological Measurement Survey (Bu72) at 25 locations in the U.S. These showed average ranges of 13 μR/hr (11.7 μrad/hr in air) for areas of approximately 25,000 km^2.

Other potential causes of error in determining annual average dose rates from structures are temporal fluctuation of exposure rates and WL values due to building materials and spatial variations within the structure. The EPA has recognized the problem resulting from fluctuations in WL levels within a structure and performs this measurement at least 4 to 6 times, preferably once each season, for a period of 100 hours or longer under conditions of normal use (Gu79). For the same reason, gamma radiation exposure rates were obtained at monitoring locations within structures for a full year by means of thermoluminescent dosimeters (TLD's) exposed for consecutive 3-month periods (Ni78).

Changes in the ventilation rate within the range normally encountered (see Section 2.4) can affect the Rn-222 concentration in room air due to structural materials by as much as an order of magnitude. The emanation rate of Rn-222 from structural materials, which directly affects the concentrations of Rn-222 and its daughters in air, has been observed to double when the air pressure changed by 2 percent (Jo75). A change in the emanation rate also affects the radiation exposure by changing the concentration of photon-emitting Rn-222 daughters that remain in the structural material, although the computed upper limit of this effect is an increase in the exposure rate by only 20 or 25 percent (Cu76, Au76). Increases in the gamma radiation exposure rate from second floor to ground floor to basement (Mo76) can be attributed to the decreased distance from the ground and basement floor and walls that are the usual sources of radiation. Higher WL values in basements than upper stories (Go72) may be due to proximity of the source in the ground or lesser ventilation rates.

2.2 Ambient Terrestrial Radiation Exposure Rates and Rn-222 Concentrations

Three broad terrestrial radiation exposure regions have been recognized in the United States: the coastal plain with a typical terrestrial gamma-ray exposure rate of 3.0 μR/hr (22.8 mrad/yr in air), the Colorado Plateau with 11.7 μR/hr (89.7 mrad/yr), and all other areas, with 5.9 μR/hr (45.6 mrad/yr) (Oa72). The external gamma-ray exposure rate is due mainly to Pb-214 and Bi-214 in the U-238 chain (99 percent of the total), Ac-228, Pb-212, and Tl-208 in the Th-232 chain (96 percent of the total), and K-40 (NC76). Both chains emit numerous energetic gamma rays. The terrestrial gamma-ray exposure rate, $\dot{X}_t$ in μR/hr one meter above flat ground is related to the radionuclide concentrations, C, in pCi/g, of these radionuclides distributed uniformly in the ground according to (Be72):

$$\dot{X}_t = 1.82\, C_{U-238} + 2.82\, C_{Th-232} + 0.179\, C_{K-40} \qquad (1)$$

Increasing the coefficient for U-238 to 1.90 from 1.82 has been recommended in response to more recent decay-scheme information (Be79).

Typical values of soil concentrations and terrestrial gamma-ray exposure rates are (NC76):

Radionuclide	Concentration	Gamma-ray exposure rate
K-40	13 pCi/g soil	2.3 μR/hr
U-238 & daughters	0.6	1.1
Th-232 & daughters	1.0	2.8
Fallout (Cs-137)	1.4	0.3
Rn-222 & daughters (in air)	0.2 pCi/l air	0.2
Total		6.7 μR/hr

Fallout from nuclear tests deposited on the ground and non-uniformly distributed with depth contributes to the exposure to a small degree, as do the Rn-222 daughters Pb-214 and Bi-214 in air. Several other naturally occurring radionuclides contribute little additional gamma-ray exposure. External exposure also results from alpha and beta particles. Radon-220 and daughter products from the Th-232 chain are also in air, usually at lower concentrations than Rn-222.

Terrestrial gamma radiation exposure 1 m above ground is almost entirely from the upper 0.3 m of soil and rock (Be72). Because of the considerable range of gamma rays in air, the source of the exposure rate is not limited to the immediate area of measurement. Local variations occur because of differences in radionuclide contents among the various soils and rock whose gamma rays are within range of the detector. Fluctuations are caused by variations in the concentrations of radon daughters -- the major sources of exposure -- in the ground near the surface and in air near the ground and by variations in the amounts of gamma-ray shielding material such as soil water and snow cover (Be74).

Average Rn-222 concentrations in air over land in the northern hemisphere are estimated to be between 0.2 and 0.3 pCi/l. This range is based on Rn-222 from typical Ra-226 concentrations in the ground emanating at the rate of 0.42 pCi/m^2sec and resulting in a world-wide average Rn-222 concentration of 0.1 pCi/l of air (Ha78a) distributed, however, mainly over land, as indicated by the very low values observed over the ocean. Corresponding concentrations of shortlived Rn-222 daughters, if near 80 percent of equilibrium (Co70), would be approximately 0.002 WL. Concentrations over land fluctuate appreciably from day to day. Emanation of Rn-222 decreases with increased atmospheric pressure, soil moisture, ground freezing, and snow cover (NC75); the extent of accumulation of Rn-222 near ground surface and equilibrium of Rn-222 daughters depends on atmospheric stability conditions; and whether airborne Rn-222 is carried by wind to or from other areas depends on wind direction.

2.3 External Gamma Radiation in Houses

Numerous major radiation exposure surveys, mostly mounted within the past 5 years, have consistently reported gamma radiation levels inside homes that are elevated when the walls are masonry and reduced when wood or prefabricated material. All but the most recent study results have been summarized in review articles by Goldin (Go72), Eadie (Ea75), Oakley (Oa72), Moeller and Underhill (Mo76), NCRP (NC75), Harley (Ha78a), and UNSCEAR (UN77). Recently available information -- some still in preliminary form -- is compiled in Table 1.

The semi-quantitative generalizations that may be drawn from these data are typified by the mean elevation and reduction factors for inside exposure rates relative to the outside proposed by Moeller and Underhill (Mo76). These factors for the ground floor are 1.3 within masonry homes and 0.7 within wood or composition frame homes. In masonry homes, exposure rates in basements are taken to be 30 percent higher than on the ground floor, and 15 percent lower on the second floor. Other ratios of inside to outside values from the cited reports and Table 1 range from 0.8 to 1.6 for masonry and from 0.7 to 1.2 for non-masonry walls. The range of values reflects the influence of factors such as type of wall and floor material, structural dimensions, and construction practices.

In the U.S., the largest data base on the contribution of normal building materials to radiation exposures within houses is for control houses surveyed in studies concerned with use of uranium-mill tailings and land reclaimed after phosphate mining. As shown in Table 1, the typical outside terrestrial exposure rate in Mesa County, Colorado -- the highest of the three terrestrial exposure regions in the U.S. -- is 8 μR/hr, and the average rate inside all houses is 6 μR/hr when 5.6 μR/hr is subtracted for the cosmic ray contribution. In Florida -- in the lowest U.S.

Table 1

Recent Measurements of Gamma-ray Exposure Rates in Buildings

Location	Type of building materials	No. of locations	Average terrestrial exposure rates, μR/hr		Reference
			Outside	Inside	
West Germany	all	30,000 dwellings (25,000 outdoor)	6.1	8.1	Ko78
	masonry		6.0	8.0	
	frame		6.6	7.8	
	prefab or timber		5.3	4.9	
Norway	all		8.4	9.1	St77
	wood (some with concrete basements)			x 0.95 (0.75-1.43)**	
	concrete			x 1.42 (1.17-2.20)	
	brick			x 1.60 (1.33-2.01)	
Poland	all		6-13 (∼8.5)		Ni78
	slag			x 1.55	
	red brick			x 1.30	
	prefab			x 1.20	
	wood			x 1.03	
Sweden	all	1,189		10.6	Mj78
	wood	405		5.7	
	brick	382		10.2	
	concrete	221		12.9	
	alum-shale concrete	181		19.3	
France	all	100 in (100 out)	9.6	9.6	Gu78
Austria -Salzburg	all	1,102 in	3.7 (0.8-14)	4.7 (1.6-16)	St78a

Table 1 (cont'd)

Location	Type of building materials	No. of locations	Average terrestrial exposure rates, μR/hr		Reference
			Outside	Inside	
United States					
-New Mexico	pumice block	9	15* (11-16)	outside +(0.5-2.6)	Do78
-Florida†	frame, masonry	294	5.6*(2-13)	outside - 0.1(-3-+2)	Gu79
-Idaho	poured concrete homes with phosphate slag	156	10*	28*	Pe78a
-Montana	concrete block homes with phosphate slag			40*	L178
-Colorado†	frame, masonry		12-15* (8-17)	11-12*(10-17)	Fr78

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* includes cosmic-ray contribution

**outside value multiplied by this number

† dwellings not built on uranium-mill tailings or phosphate-mineral land

terrestrial exposure region -- the average outside terrestrial exposure rate of 2.2 μR/hr (at a cosmic ray contribution of 3.4 μR/hr) is almost identical with average values in homes with both types of wall materials. Because of the efforts made to assure that control houses were not located on or near uranium-tailings backfill in Colorado and phosphate-bearing land in Florida, some houses with higher gamma exposure rates due to wall or floor materials may have been omitted from these groups.

Other data consistent with the estimates by Moeller and Underhill are in studies of smaller groups of houses in Boston (Ye72), east Tennessee (Lo71), and the New York metropolitan area (Ha78a). In east Tennessee, despite the indigenous Conasauga shale with elevated uranium content, external terrestrial exposure levels were on the average only 6 μR/hr, typical of exposure rates in the intermediate ("non-coastal") exposure region. Exposure rates averaged the same within houses with masonry walls (some of which were built with brick and concrete that may contain indigenous shale) as outside. Radiation exposure rates in tall masonry buildings in Boston were almost constant from the ground to the twenty-third floor.

A very simple model for a 1-floor-plan home in the U.S. is consistent with the typical observed reductions and elevations of radiation exposures. For wooden walls in frame construction, the flux of 1-MeV gamma rays passing through 4 g/cm^2 of building material at an attenuation coefficient of 0.06 cm^2/g is reduced by 21 percent. Within radionuclide-bearing walls that are infinitely thick to gamma rays, the formula for exposure within an infinite radiation source can be applied:

$$\dot{X}_{\infty} = 2.43E_{U-238}C_{U-238} + 2.43E_{Th-232}C_{Th-232} + 2.43E_{K-40}C_{K-40} \qquad (2)$$

where the units of $\dot{X}$ and C are the same as in equation (1), and E is the gamma-ray energy per disintegration. For the U-238 chain and the Th-232 chain, recently published values of gamma ray energies and decay fractions (Ko77) yield respective values for E of 1.72 and 2.36 MeV/disintegration, while that for K-40 (NC76) is 0.156 MeV/disintegration. Hence, the coefficients for the three concentration values are 4.18, 5.73, and 0.379 μR/hr per pCi/g, respectively. These are somewhat more than twice the values of the coefficients for the exposure rate from outside terrestrial radionuclides (see equation 1), the case of an infinite hemisphere. Because of the influence of the different media -- soil and air -- in the two hemispheres on the buildup factors, the coefficients for the soil hemisphere are approximately 0.48 of those for a sphere at energies of 1.0-2.5 MeV, and between 0.40 and 0.47 from 0.2 to 1.0 MeV (Be72a). Krisiuk et al. have given coefficients that are approximately 30 percent higher for U-238 and Th-232 (Kr71a), possibly based on earlier decay schemes. This 2-fold elevation above outside values for the same radionuclide levels is an upper limit with restricted application, e.g., to inside rooms in multi-story buildings. In U.S. homes, walls and floors are more usually 10 cm thick (rather than the 40 cm at a density of 2 g/cm^3 that would approach an infinite medium), and ceilings and roof rarely are significant radiation sources.

To estimate radiation exposure from known concentrations of the terrestrial radionuclides in walls more realistically, Koblinger computed the effect of wall thickness with a Monte Carlo program (Ko78). Within a room 4 x 5 x 2.8 m, completely surrounded by walls, floor, and ceiling of uniform radionuclide content, the coefficients for infinite wall thickness, extrapolated from his values, are consistent with those in equation (2), while the ones for 10-cm walls are approximately two-thirds of the infinite-thickness values. One can infer that the outside exposure rate would be reduced to one-third its initial value by walls and floor under identical conditions. In homes where walls are 10 cm thick and only approximately two-thirds of the surface area -- walls and floor but not windows and roof -- is a source of elevated radiation levels, the inside exposure rate would be

$$\dot{X}_h = 0.44\dot{X}_\infty + 0.33\dot{X}_t \tag{3}$$

where the subscripts h and t refer to terrestrial radiation exposure inside and outside, respectively. If a radiation exposure index for building materials, $\dot{I}$, is defined as 0.5 $\dot{X}_\infty$ in order to place exposure rates from building materials and the ground on a common basis, then

$$\dot{X}_h = 0.9\ \dot{I} + 0.3\ \dot{X}_t \tag{4}$$

If the concentrations of terrestrial radionuclides in building materials and the ground are the same, the inside exposure rate according to equation (4) is 1.2 times the outside value.

Elevated radiation exposures can also be caused by radionuclide-containing materials within the house. Among these are wallboard constructed with phosphogypsum (Fi78, OR72), and glass fiber insulation made of the calcium silicate byproduct in the thermal process for phosphorus production (He78). Brick and stone fireplaces and ceramic tiles are other potential sources.

Some consistently elevated radiation exposure rates in European houses have been attributed to specific materials. Hultqvist (Hu65) and Mjones (Mj78) have shown that buildings constructed of concrete that contains expanded alum shale have inside radiation exposure rates that average 11-12 μR/hr above outside values and are in some cases much higher. A few of the highest measurements by Hultqvist in brick-walled houses in Sweden, and by Stranden (St78) in Norwegian concrete buildings also were equal to or slightly more than 10 μR/hr above outside values. All other surveys that report inside and outside rates, incremental inside rates, or inside rates for which outside companion values could be estimated gave elevations well below 10 μR/hr.

Current studies in Idaho (Pe78a), Montana (Ll78), Alabama (Ma78), and in this project have encountered elevated radiation exposures in buildings constructed with concrete of which one constituent is the calcium silicate slag from the thermal phosphorus process. In Soda Springs and Pocatello, Idaho, and Butte and Anaconda, Montana and their environs, radiation exposure levels within houses constructed with this material averaged 30 and 40 μR/hr, respectively, as shown in Table 1. Similarly elevated exposure rates observed in Atlanta, Georgia, are given in section 3.3. No other measurements in the U.S. have been reported with such elevated values, with the exception of houses built on uranium-mill tailings and phosphate-mineral lands.

2.4 Radon Concentrations and WL Values in Houses

Concentrations of Rn-222 and its short-lived daughter products in houses have been measured in the range of 0.01 to 18 pCi/l in a number of surveys throughout the world. Average values, and in some cases ranges and concentrations outside for comparison, have been reported in the reviews by Moeller and Underhill (Mo76), Eadie (Ea75), Goldin (Go72), NCRP (NC75), and UNSCEAR (UN77). Recent results are summarized in Table 2. Concentrations in wooden frame houses are generally comparable to outside values, while masonry houses may have elevated levels. Highest concentrations are found in basements. Ventilation has a controlling influence on radon and radon-daughter concentrations in houses, in that radon-222 accumulates in areas without air circulation where doors and windows are opened infrequently, and is dissipated by good ventilation (Ha67, Ca75, Wi78). Atmospheric pressure changes greatly affect Rn-222 concentrations: a decrease from 760 to 746 torr doubled Rn-222 levels in air within an unventilated room, while an increase over the same range reduced levels to one-half (Jo75).

Radon-222 daughters are usually not in equilibrium with each other and their gaseous parent because of air movement and deposition of the particulate daughters on surfaces (Po78). Ratios of Rn-222:Po-218:Pb-214:Bi-214 (Po-214) such as 1.0:0.9:0.4:0.2 are encountered in normally ventilated rooms (UN77). For this ratio, the fractional WL value relative to equilibrium, on the basis of 0.10, 0.51, and 0.37 WL per 100 pCi/l for Po-218, Pb-214, and Bi-214, respectively (UN77), is 0.4. Fractional WL values relative to equilibrium above 0.5 have not been measured in houses (UN77). A study of the effect of ventilation showed that the fractional equilibrium was 0.4 in an unused home, where the air turnover rate from leakage alone was approximately 0.5 per hour, but decreased to 0.1 when the turnover rate was increased to 5 per hour by air conditioning and home use (Wi78).

Because of the extreme variability of Rn-222 and daughter concentrations in buildings due to fluctuations in outside air, exhalation rates from building materials and the ground beneath the house, and air turnover, only long-term measurements can determine average concentrations in building air. Many of the reported values are based on one or two observations that have little validity for estimating average internal dose. To obtain more representative results, repeated sampling periods of 100 hours or longer were used where possible in the surveys of houses in the U.S. that had significantly elevated Rn-222 concentrations in air due

Table 2

Recent Measurements of Rn-222 Concentrations and WL Values in Buildings

Location	Type of building	No. of Locations	Rn-222 daughter concentrations, pCi/l or WL Outside	 Inside	Reference
Sweden	wood			2.7 pCi/l	Sw78
(1-family)	wood and alum shale concrete cellar			5.4 (<0.7-10) pCi/l	
	alum-shale concrete			7.3 (4.0-11) pCi/l	
	wood & brick facade			11.1 (5.9-15) pCi/l	
(multi-family)	concrete			4.2 (1.5-18) pCi/l	
	concrete & sand concrete			2.3 (0.9-3.9) pCi/l	
	concrete & sand concrete & alum-shale concrete			4.6 (2.3-11) pCi/l	
Austria -Salzburg	all		0.22 pCi/l (<0.04-1.29)	0.6 (<0.05-5.2) pCi/l	St78
United States					
-Colorado	all*	29		0.0072 WL ×÷1.7 (1σ)	Pe77
-Florida	all*	50		0.004 (0.001-0.039)	Gu79
-New York	all residences			0.002-0.01 WL	Ge78
-N. Carolina	office buildings	32		0.003 (0.0004-0.03) WL	Al74
-Idaho	poured concrete homes with phosphate slag	107	∿1 pCi/l	0.0053(0.0006-0.05) WL	Pe78a
	normal			0.005 WL	
-Montana	concrete block homes	72		∿0.012 (<0.005->0.1) WL	Ll78
-New Mexico	pumice block	9		0.004 (0.002-0.014) WL	Do78
	frame/stucco	5		0.003 (0.002-0.014) WL	

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* not constructed on uranium-mill tailings or phosphate-mineral land

to location on uranium-mill tailings or phosphate land (Gu79).

The houses used as controls in these two surveys yielded the wide ranges of WL values given in Table 2. The 29 structures in Mesa County, Colorado, showed a log-normal distribution with a log-mean value of 0.0072 WL and a geometric standard deviation of $\overset{\times}{\div}1.7$ (Pe77); the observed distribution suggests that 16 percent of WL values measured in such houses will be above the upper 1-sigma value of 0.012 WL, and 2.5 percent will be above the 2-sigma value of 0.021 WL. Both frame and masonry houses are included in this sample because external radiation exposure rates did not differ noticeably among them. The wide range of values is ascribed mainly to ventilating practices (Pe78a). The outside value was not given in the report, but typical values of 0.003 WL have been measured (Fr78). On this basis, an extensive survey would find numerous houses in this area for which Rn-222 daughter levels in inside air may exceed by 0.01 WL the average level in outside air.

In 50 control houses in Hillsboro and Polk Counties, Florida, the log-mean value was 0.004 WL and the range was from 0.001 to 0.039 WL. On a log-normal graph, the values yielded a curve that is concave upwards. Although three of the four highest WL values were in masonry houses, masonry and non-masonry houses did not constitute distinct WL categories. Note that geometric means, although apparently more appropriate, are numerically lower than arithmetic means. The curved distribution line may indicate either the presence of two Rn-222 sources, for example outside air and building materials, or two distinct types of ventilating conditions. A similar distribution about the log-mean value existed for the North Carolina measurements given in Table 2.

The relation of the Rn-222 concentration within a building to the exhalation rate from walls and floor, its decay in air, and the ventilation rate is:

$$\frac{dC_{Rn}}{dt} = \frac{SI}{V} - \lambda_{Rn} C_{Rn} - \lambda_a (C_{Rn} - C_o) \qquad (5)$$

where C_{Rn} : radon concentration in the room, pCi/m^3

C_o : radon concentration outside, pCi/m^3

t : time for change in concentration inside, hr

S : surface area for radon exhalation, m^2

I : inward flux of radon, $pCi/hr\ m^2$

V : volume of inside space, m^3

λ_{Rn} : decay constant of Rn-222 ($0.00755\ hr^{-1}$)

λ_a : turnover constant of inside air, hr^{-1}

When the concentration is constant,

$$C_{Rn} = \frac{1}{\lambda_{Rn} + \lambda_a} \left(\frac{SI}{V} + \lambda_a C_o\right) \qquad (6)$$

The inward flux of radon from a wall and/or floor surface can be written as

$$I = 10^6 \, C_{Ra} \lambda_{Rn} f d \rho \qquad (7)$$

where C_{Ra} : concentration of Ra-226 in wall and/or floor, pCi/g

f : fractional exhalation of Rn-222 from the material

d : thickness of wall and/or floor, m

ρ : density of wall and/or floor, g/cm^3

When equation (7) is combined with equation (6),

$$C_{Rn} = \frac{1}{\lambda_{Rn} + \lambda_a} \left(\frac{10^6 C_{Ra} \lambda_{Rn} f d S \rho}{V} + \lambda_a C_o\right) \qquad (8)$$

Under usual ventilating conditions, the decay constant of Rn-222 is so much smaller than the air turnover rate that it can be omitted in the denominator. If concentrations of Rn-222 are in units of pCi/l,

$$C_{Rn} = \frac{10^3 C_{Ra} f d S \lambda_{Rn} \rho}{V \lambda_a} + C_o \qquad (9)$$

The Rn-222 concentration in a typical frame house built on a concrete slab, computed with the above equation, is 0.036 pCi/l per Ra-226 concentration of 1 pCi/g in the concrete. This result is for a fractional exhalation of 0.05, slab thickness of 0.1 m, density of 2.3 g/cm^3, room height (V/S where S is the floor surface only) of 2.4 m, and air change of 1.0 per hour. The corresponding radon-daughter value at 40 percent of equilibrium is 0.00014 WL. Exhalation fractions (emanating powers) of brick and concrete have been reported as typically 0.5 to 2 percent, with a few values near 5 percent (Mo76, Pe78). Too few values are available for these to be definitive, but the large change in exhalation produced by a small change in atmospheric pressure suggests that this fraction is small. Air turnover rates in the U.S. have been characterized regionally as between 0.5 and 1.5 per hour for normal house use (Ha73). Air exchange could be much greater in well-ventilated buildings and much smaller in rooms that are little used within tightly constructed buildings.

If the walls also contain Ra-226, their surface areas must be included in S. This can increase the factor S/V from 0.4 to 0.7 m^{-1} in a medium-sized 1-floor house, and to as much as 2.5 m^{-1} in a room entirely surrounded by radium-bearing walls, floor, and ceiling. In these cases, however, exhalation from the walls and ceiling is usually both inward and outward, so that these additional surface areas must be divided by two. Hence, a relatively large factor S/V is approximately three times the value used above, i.e., 1.2 m^{-1}, and the corresponding radon-daughter concentration would be 0.0004 WL at a Ra-226 concentration of 1 pCi/g.

At this Ra-226 concentration in the slab, more Rn-222 would diffuse through the slab from the ground than emanates from the slab. The Rn-222 concentration of 0.036 pCi/l computed above results from an exhalation rate from the slab of 87 pCi/m^2hr while the typical emanation rate from the ground is 1,500 pCi/m^2hr (i.e., 0.75 atom/cm^2sec) (Wi72). All of this Rn-222 may reach the room through ducts, drains and cracks, or approximately 40 percent (600 pCi/m^2hr) would diffuse through 10 cm of concrete (Cu76a). Thus, the concentration in room air of Rn-222 from the ground would be between 0.24 and 0.62 pCi/l (0.001-0.002 WL). In a basement partially or completely below ground, the factor S/V could be approximately three times as great as for a slab, tripling the Rn-222 concentration. Emanation rates from the ground vary considerably (Wi72), but such diffusion from ground through building materials into the basement or ground floor undoubtedly contributes to the higher concentrations measured there.

The Rn-222 concentration in basement air from walls built with concrete blocks that contain phosphate slag is similar to the above values. The unusually light blocks that could be produced with the slag weighed 22 to 28 lb (9.9-12.6 kg) depending on the fraction of slag in the block, for dimensions of 16" long x 8" high x 4" thick (41 x 20 x 10 cm). Their volume density is thus approximately 1.4 g/cm^3. In a basement 7 m x 14 m and 2.4 m high, use of equation (9) and the factors applied previously (0.05 fractional exhalation, 1 air change per hour) results in the following elevation of Rn-222 in air:

$$C_{Rn} - C_o = \frac{10^3 x1x0.05x0.15x2.4x2(7+14)x0.00755x1.4}{7x14x2.4x1}$$
$$= 0.034 \text{ pCi/l air per 1 pCi Ra-226/g block}$$

Radon daughter concentrations at 40 percent of equilibrium would be 0.00014 WL.

Thus, elevated values of 0.0001 to 0.0004 WL can be expected per Ra-226 content of 1 pCi/g in buildings with masonry walls and/or floors under normal ventilation. At the same time, the outside air may typically contribute Rn-222 daughter products to the extent of 0.002 WL, and the ground, 0.001-0.006 WL, and these values may fluctuate widely. Furthermore, ventilation rates may be 5-fold higher or lower than 1 air turnover per hour (UN77), raising or lowering the Rn-222 concentrations accordingly and also affecting equilibrium between Rn-222 and its daughters. Radon-222 may also be introduced through other sources, notably Ra-226 in water and gas that carry it from the ground (Ge75).

Among the recent surveys summarized in Table 2, only the Swedish measurements (Sw78) show significantly elevated Rn-222 concentrations in building air that may be attributed to brick and concrete structural materials. Low ventilation rates are believed to have been partially responsible for these elevated values and to have caused the higher WL values in North Carolina (Al74). More detailed studies are required to distinguish among the sources of Rn-222 concentration and WL values at the upper ranges of the other data. The above calculations suggest that Ra-226 concentrations in building material may have to be greater than in the ground by a factor of 20 or more before WL increments due to building materials can be determined reliably.

2.5 Elevated Radionuclide Concentrations in Building Materials

The construction materials and the potential constituents of these materials that are listed in Table 3 have been reported to contain elevated radionuclide levels. Materials and constituents were included in the table if the concentrations of Ra-226, Th-232, and K-40 were above the respective typical concentration ranges in soil and rock of 0.5-2, 0.2-2, and 2-30 pCi/g (NC76). The medium category of concrete and brick in the test survey at Atlanta (see Section 3.3) were in this range, although toward the high end.

The tabulation suggests that these materials can contain elevated radionuclide levels from constituents that occur in nature such as granite, pumice, and shales, or are byproduct materials such as "red slime" in bricks or steel slag, steel sand, and phosphate slag in concrete. Wall board manufactured from phosphogypsum -- the byproduct of phosphate production by the sulfuric acid process -- also can contain elevated radionuclide levels. Radium-226 concentrations in phosphate rock are in the range of 26 to 74 pCi/g in Florida, Montana, Idaho, Wyoming, and Utah (Me68, He79), only 3-7 pCi/g in Tennessee, but 130 pCi/g in South Carolina (Me68). Thorium-232 levels in phosphate rock are only 0.8-2.1 pCi/g (Me68). Not all of these may have been used in building materials; for example, no such use of South Carolina phosphate rock has been reported. Some fly ash utilized in concrete manufacturing has been found to contain elevated Ra-226 and Th-232 levels (Ko78), but values are not included in Table 3 because the fraction used in the mixture has been so small that the concentration in the resulting material would not be significantly elevated (see Section 3.3).

Utilization of the indicated materials that cause elevated radiation exposures in structures has been observed in Germany, the United Kingdom, and the USSR. Phosphogypsum wall board from Florida phosphate rock has been produced in Japan (Fi78). Elevated exposure rates and Rn-222 concentrations in Sweden were observed in buildings constructed with alum shale concrete (Mj78, Sw78).

In the United States, the only building material that so far has been associated with elevated radiation exposures and possibly elevated Rn-222 concentrations is phosphate slag. A distinction is made here between

Table 3

Elevated Radionuclide Concentrations in Construction Materials and their Constituents

Location	Material	Radionuclide Concentration, pCi/g Ra-226	Th-232	K-40	Reference
West Germany	Red slime brick	2.5-6.7	3.9-10	8-13	Ko78
	Pumice brick	0.7-3.6	1.1-4.6	13-30	
	Steel sand & slag bricks	1.2-3.2	0.6-5.6	3-16	
	Cement	0.3-5.3	0.3-5.2	<0.5-7	
	Byproduct gypsum	7-28.	<0.5	<0.8-6	
United Kingdom	Phosphogypsum	17 (Ra equivalent)			Ha71
USSR	Granite	3.0	4.5	40	Kr71
	Phosphate slag	6.1	0.5	4	
	Slag pumice	5.5	0.5	5	
United States	Phosphogypsum (FL)	33			Fi78
	(ID)	25			
	Phosphate slag (FL)	56			
	Phosphate slag (ID)	35-41			Bo77
	Phosphogypsum	12			
	Phosphate slag (TN/FL)	20.8			Wi75
	Concrete blocks w phosphate slag	3.8-8.2			
	Phosphate slag (FL)	56			He79
	Phosphate slag (ID)	32			
	Phosphate slag (MT)	28			
	Pumice	5.6-6.1	3.7-4.0		Do78
	Blocks w pumice	2.2-3.4	1.2		
	Concrete w alum shale (old)	35			Fi78
	(new)	9			
	Volcanic tuff	4-7			

material used within the structure, e.g., in walls and floors, as compared to fill beneath and around the house in the case of uranium-mill tailings and phosphate-mining backfill. Some uranium-mill tailings may have been used in actual building construction, but such cases apparently have not been considered separately (He78). Shipment of Florida phosphogypsum to a manufacturer of wallboard, partition blocks, and plaster in New Jersey has been reported (Fi78), but no structures were identified in which this phosphogypsum was used. No elevated gamma radiation exposure rates and Rn-222 concentrations were found in buildings constructed with pumice stone despite its higher radionuclide content (see Sections 2.3 and 2.4).

Between 300 and 400 million tons of slag were produced between 1896 and 1976 as a byproduct of phosphorus manufacture in the U.S. by the thermal process (He79). Much of this calcium silicate has been used in agriculture as soil nutrient and in general construction as coarse or fine aggregate (i.e., as gravel or sand) for road and railroad beds (Pe78a), fill, septic-tank drain fields (Jo78) and concrete manufacture; the remainder is presumably accumulated in slag piles near thermal process phosphorus production plants. Within the immediate past, three such plants were in operation in Florida, one in Alabama, three in Tennessee, two in Idaho, and one in Montana; other plants previously operated in New Jersey, New York, Pennsylvania, the District of Columbia, Florida, Tennessee, South Carolina, Iowa, and Idaho (He79). Of particular interest to this review is the use of the slag in producing concrete for building construction, if the slag is derived from phosphate rock that contained elevated concentrations of Ra-226.

Concrete construction materials with elevated radiation levels that are attributed to incorporated slag from this source have been found in Montana, Idaho, Georgia, and Alabama. In Montana, the slag was used to manufacture concrete blocks and prestressed beams and slabs in the late 1950's (Ll78). In Idaho, the slag was used both as fine and coarse aggregate, so that it constituted as much as 89 percent of the poured concrete that was manufactured with it (Pe78a, Bo77). The most widespread use in building construction appears to have occurred with the slag produced by a thermal-process plant in northern Alabama because an expanded form was developed that was particularly desirable for producing light-weight concrete blocks.

Production of expanded slag predominated from 1953 to 1968, when it was ended for economic reasons and only quenched slag continued to be sold. Phosphorus production at the Alabama plant terminated in 1975, but slag continued to be sold until all shipments were halted in December 1978. A slag pile of 3 - 4 million tons remains in a ravine near the plant (Ma78).

According to records dating back to 1953, the slag was sold by the Alabama plant to 160 construction or building material companies located mainly in Alabama, Mississippi, Tennessee, Georgia, and Kentucky; only 2,000 tons were sold beyond these states (Ma78). It is believed that the main use of the slag was in concrete block manufacture. Expanded slag constitutes 80 - 90 percent by weight of light-weight blocks that were made with it during the period 1953 - 1968; quenched slag constitutes 30 - 40 percent by weight of blocks made with it, mostly after 1968.

For phosphorus production, Tennessee and Florida ores were used by the Alabama plant in the ratio 63:37, averaged over the years 1962 to 1974. At Ra-226 concentrations of 4 pCi/g for the former and 65 pCi/g for the latter (Wi75), the furnace charge for phosphorus production would contain 27 pCi/g. As indicated in Section 3.3, the quenched slag had Ra-226 concentrations averaging 28 pCi/g. A concrete block formed with quenched slag would contain approximately 19 pCi/g, but values of only 4 and 8 pCi/g were measured in concrete blocks made from this material in 1974 (Wi75). Lightweight blocks that are believed to be made with expanded slag contain 21 pCi/g, as indicated in Section 3.3; this is consistent with the predicted value for lightweight block, at 80 percent slag, of 22 pCi/g. Both the ratio of ores and the fraction of slag used in concrete blocks, however, may have been varied.

Other uses of the slag in building construction are still being looked for, although they are believed to be minor relative to the production of concrete blocks. Some slag was used in cement, although only to the extent of 3 percent of the mix (Ma78), which represents a minor contribution of Ra-226 (i.e., an elevation by approximately 0.8 pCi/g). Other uses that need to be considered are in poured concrete, as fill beneath and around houses, and in mortar and decorative facing. Use of slag for producing glass wool insulation has been under development in Washington (He78). In Florida, it may be used as ballast on flat roofs (Jo78).

Thus, building materials that contain naturally occurring constituents with noticeable radionuclide levels, such as clay and gravel, have so far in the U.S. shown only the normal range of radionuclide concentrations. The elevated exposure rates and WL values found in Swedish homes and the elevated terrestrial exposure rates and WL values found at some U.S. locations suggest that such building materials with elevated radionuclide concentrations may be encountered in a nationwide survey. A small number of building material samples with such elevated levels were found in the present study (Section 3.3). Among byproducts used in building materials, only phosphate slag is known to be at elevated levels in the U.S., but nationwide survey of radiation in structures would be desirable to search for structures built with other such materials, notably those listed in Table 3.

2.6 Radiation Dose to Persons from Building Materials

The currently available information is insufficient to compute with any reliability the incremental population dose equivalents in structures due to building materials or to estimate the number of persons exposed to significantly elevated radiation from these materials. Some estimates are made here based on the information in the preceding Section and Section 3.3 to indicate the magnitudes of the number of exposed persons in the United States and their doses that need to be delineated by a survey of radiation in structures. For this purpose, four dose categories are considered in terms of building material types and radionuclide contents:

- materials that contain so little radioactivity that they can be ignored as sources of gamma radiation and Rn-222, and that, moreover, act as radiation absorbers when used in walls and floors;
- indigenous materials with radionuclide content similar to the ground beneath the structure that cause some elevation of gamma radiation exposure due to proximity and some elevation of WL values due to exhalation of Rn-222 daughters into building air;
- natural materials that contain significantly elevated radionuclide concentrations relative to the ground beneath the structure; and
- byproduct materials as defined under the Resource Conservation and Recovery Act that contain significantly elevated radionuclide concentrations.

With respect to the first two categories, the most extensive survey of gamma radiation exposure rates in structures, recently completed in the German Federal Republic (Bu78, Ko78), showed on the average a small decrease inside residences with wooden or prefabricated walls, and a larger increase inside residences with masonry walls. The annual average increments were -3 mR (-2 mrem) in the former and +17 mR (+10 mrem) in the latter; for all dwellings, the average increment was +16 mR (+9 mrem) (Ko78). The calculation of gamma-ray exposure rates in U.S. homes cited in Section 2.3 predicts an annual average increment of -1.6 mrem at an average occupancy factor of 0.7, and -3.2 mrem for the full year spent in various buildings as well as outside (Mo76). The homes considered in the calculation were constructed mostly with wooden or prefabricated wall material. More recent statistics suggest that use of masonry walls and brick, stone, concrete, and stucco facing has increased rapidly in recent years from the 43 percent value used in the calculation to 70 percent in 1975 (Ho76). On this basis, the calculation, which in highly simplified form indicates an average annual increase of approximately 8 mrem for masonry homes and a corresponding decrease of 8 mrem for wooden houses, yields an overall average annual increase of 3 mrem in the home and of 4 mrem in all structures. The average terrestrial exposure rate of 51 mR/yr (44 mrad/yr in air) calculated for the U.S. (NC75) is very similar to the West German average of 53 mR/yr based on 25,000 measurements in the survey (Ko78). The lower annual increment from building material predicted for the U.S. may reflect different building practices or use of inappropriate coefficients in the calculational model. The measurements in Germany found differences in average exposure rate elevations among several building materials, but the entire group of exposure rate values was relatively closely clustered and normally distributed except for approximately 4 percent of the highest inside measurements in the range of 16 to 28 μR/hr (Bu78).

Measurements and calculational models both suggest that gamma radiation exposure rates are not usually elevated to a significant extent in structures built with materials that have the same radionuclide content as the ground nearby. Equation (4) indicates that an outside exposure rate of 25 μR/hr (190 mrad/yr in air) would be required to cause an elevation of 5 μR/hr within a structure. The various brief and scattered surveys in the U.S. have not shown any settled areas where the terrestrial gamma radiation exposure rate reaches 190 mrad/yr (NC75).

On the other hand, exposure rate elevations within structures by 5 μR/hr or more would be expected occasionally from naturally occurring building materials that have significantly elevated radionuclide concentrations relative to the nearby ground. Alum shale used in concrete manufacture in Sweden (see Table 1) caused such increases. Although significantly elevated values due to natural materials have apparently not been reported for U.S. structures, some of the brick and concrete samples examined in the present study (see Section 3.3) contained radionuclides at concentrations so much above normal that approximately a doubling of outside exposure rates is predicted if this material were used for all walls and floors. Based on the infrequency with which the materials with elevated radioactivity were encountered, the resulting exposure rate elevation of approximately 6 μR/hr (30 mrem/yr) relative to the outside would only occur in approximately 1 percent of all structures. As indicated in Section 3.3, the elevated radioactivity in brick was traced to a pit from which at least some of the clay for these bricks had been obtained. For the purpose of this estimate, an elevation in dose equivalent rate by 30 mrem per year is assumed for 1 percent of all dwellings, although both numbers are highly uncertain because they depend on the use of specific sources of constituents such as clay or gravel that happen to be at a relatively elevated radionuclide content.

The summary in Section 2.5 indicates that phosphate slag used in concrete is the only material controllable under the Resource Conservation and Recovery Act that is currently known to cause significantly increased gamma ray exposure rates when used as structural material in the U.S. Use of phosphogypsum in wallboard is suspected, but no structures have been identified. Byproduct materials for which elevated levels were observed in other countries (see Section 2.5) have so far not been associated with observed elevated levels in the U.S.

At present, approximately 160 buildings constructed with concrete that contains phosphate slag have been found in Idaho (Pe78a), 110 in Montana (L178), 5 in Georgia (Section 3.3) and 16 in Alabama (Ma78). Except in Georgia, most of the buildings are homes. The total number of such buildings may be 500 in Idaho (Pe78a), 150 in Montana (L178), and many thousands (see below) in the southeastern U.S. The slag has been used mostly in the immediate vicinity of one thermal-process phosphorus plant in Montana and two in Idaho, and over a much wider area around the plant in northern Alabama. A moratorium on sale of such slag has been agreed to by the plant in Montana (L178); Idaho has prohibited use of this slag in buildings (Pe78a); and the plant in Alabama ceased all shipments in December 1978 (Ma78).

On the basis of estimates made in Section 3.4 of the number of buildings constructed with 378,000 tons of slag shipped to the Atlanta area, the entire

2.8 million tons of slag estimated to have been sold by the Alabama plant to building material manufacturers in the period 1953 to 1978 (Ma78) could have been used to construct 74,000 homes and 4,400 non-residential buildings. These numbers are uncertain because it is not known at present whether all of the material was used in concrete blocks, what the various fractions of slag per total block were, and what actual use was made of these blocks. At an occupancy of 3.7 persons per home, 300,000 persons would be exposed in the homes in the southeast, Idaho and Montana. By utilizing an occupancy factor of 1.0 for these persons in the dose calculation, exposure in non-residential buildings is included, although such exposure would not necessarily or even probably pertain to the same persons.

Exposure rates from use of this material depend on the Ra-226 content of the phosphate slag, the percent used in concrete, and the amount of concrete per structure. In homes in the southeastern U.S., where the phosphate slag appears to have been used generally as concrete blocks in basement walls, the average gamma ray exposure rate was estimated to be typically 12 μR/hr above outside levels (see Section 3.4). Measured elevations of exposure were approximately 20 μR/hr in non-residential structures in Georgia (Section 3.4), 20 μR/hr elevated in Idaho residences, and 30 μR/hr elevated in Montana residences (see Table 1). In Idaho and Montana, the higher Ra-226 content of slag is probably responsible for the higher exposure rate elevations, while the nonresidential structures in Georgia use more concrete. To be conservative, an exposure rate elevation of 20 μR/hr (100 mrem/yr) is estimated from this information for a population of 300,000 persons.

A recently initiated survey of structures in the southeastern U.S. that were built with these concrete blocks containing phosphate slag should soon provide additional exposure rate information (Ma78). Delineation of exposures from any additional byproduct materials that cause significantly elevated radiation exposure rates will have to await further searches such as the nationwide survey recommended here.

No measurable elevation in WL value due to building material is expected for the 30 percent of 1-family homes constructed of wood and prefabricated material with very low Ra-226 content. This percentage may be applied to the entire U.S. population (i.e., including those in multi-family structures) without large error because more than 90 percent of the population lives in single-family homes (Ho76). A distinction must be made, however, between Ra-226 in building materials and other causes of elevated WL values within a structure, such as emanation directly from the ground, because elevated WL values in room air apparently occur widely in the absence of Ra-226 in building materials.

The geometrical configurations of walls and floors relative to room volume considered in Section 2.4 suggest that typical Ra-226 concentrations of 1 pCi/g in building material result in values between 0.0001 and 0.0004 WL if the exhalation fraction is 0.05 and there is 1 turnover of air per hour. For estimating dose equivalents, it is assumed that 70 percent of the population is exposed to an intermediate value of 0.00025 WL due to building materials under these typical conditions. An occupancy factor of 0.95 is used to include exposure in structures other than homes. At a conversion factor of 78 rem/yr per WL, the dose to the lungs of a person under these condition is 19 mrem/yr. Because the normal range of Ra-226 concentrations is as high as 2 pCi/g and the normal rate of air turnover as low as 0.5 per hour, values could be as high as 0.0004 x 4 = 0.0016 WL (120 mrem/yr). Elevation of WL values even to this extent would not be readily detected at a typical ambient value of 0.002 WL because of the fluctuations of Rn-222 daughter concentrations in room air in response to fluctuations in outside air.

If 1 percent of all structures were built with naturally occurring material that contained Ra-226 at the concentration of 3.5 pCi/g found in the high-exposure-rate category of brick (see Section 3.4), the WL values in these structures would be correspondingly higher by the factor 3.5, i.e., at 0.00088 WL (65 mrem/yr), than the typical structure considered above. This value may be 3-fold higher if the ratio of surface area of radium-bearing material to room volume were greater and the ventilation rate less.

In the dwellings in the southeastern states that are believed to have basement walls of phosphate-slag concrete blocks, the calculation in Section 2.4 predicts 0.003 WL (230 mrem/yr) at 1 air turnover per hour and a Ra-226 concentration of 21 pCi/g. If the concrete has Ra-226 levels as high as 35 pCi/g and is used in the floor as well as in walls, and the air turnover is only 0.5 per hour, then the Rn-222 daughters may be at concentrations in room air 13 times as high, or at 0.038 WL (2.9 rem/yr). This represents an upper limit except for conditions of extremely restricted air circulation. Approximately 300,000 persons are estimated to be exposed to 0.003 WL while 3,000 persons are estimated to be exposed at an order of magnitude higher dose equivalent. An occupancy factor of 1.0 is used as indicated above to account for exposure in nonresidential structures also.

The elevation above outside values in population organ dose equivalents due to building materials in structures estimated according to the above categories are as follows for a U.S. population in 1977 of 217,000,000:

	population organ dose equivalents, million person-rem/yr	
	external radiation	Rn-222 daughters
ambient (51 mR/yr terrestrial and 0.002 WL)	6.4	34
elevation from:		
typical structures and materials	0.9	3
natural material, high radionuclide content	0.06	0.1
byproduct material, high radionuclide content	0.03	0.08

This summary suggests that typical structures built with materials that contain the terrestrial radionuclides need to be considered in determining population organ dose equivalents, but that the currently known or estimated occurrences of significantly elevated exposure rates and WL values do not add appreciably to the total. Increases in individual dose equivalent rates to persons in the two latter categories, however, appear sufficiently large in some instances to confirm the need for surveys to identify structures with elevated radiation and WL values, measure their exposure rates and WL values, and take preventive or remedial action where appropriate.

2.7 Preventive and Remedial Actions

If appropriate from a cost-benefit evaluation, the most effective preventive action is prohibiting the use of building materials that will increase external gamma radiation or WL values within a building beyond a specified value. The states of Idaho and Montana have, by administrative order and agreement with suppliers, respectively, prohibited use of phosphate slag in homes; the EPA is proposing such prohibitions under the Resources Conservation and Recovery Act. A detailed survey would be required for this purpose in the U.S. to evaluate those construction materials and their constituents that are believed to contain elevated radionuclide concentrations, particularly Ra-226. The materials listed in Table 3 are recommended for first consideration.

As an example of the way in which concentrations of radionuclides can be related to limiting exposure rate elevations, if the latter is designated $\Delta\dot{X}_h$, then from equation (4)

$$\Delta\dot{X}_h + \dot{X}_t \geq 0.9\,\dot{I} + 0.3\,\dot{X}_t \qquad (10a)$$

and

$$\dot{I} \leq 1.1\,(\Delta\dot{X}_h + 0.7\,\dot{X}_t) \qquad (10b)$$

Thus, if $\Delta\dot{X}_h$ is set at 5 μR/hr and $\dot{X}_t$ at a typical location is 6 μR/hr, then $\dot{I} \leq 10$. Because $\dot{I}$ has been defined in Section 2.3 to correspond within a structure to $\dot{X}_t$ outside, it can be related to radionuclide concentrations in structural materials as $\dot{X}_t$ was related to terrestrial radionuclides in the ground in equation (1):

$$1.82\,C_{U\text{-}238} + 2.82\,C_{Th\text{-}232} + 0.179\,C_{K\text{-}40} \leq 10 \qquad (11a)$$

where C is in pCi/g. This can be written as

$$\frac{C_{U\text{-}238}}{5.5} + \frac{C_{Th\text{-}232}}{3.5} + \frac{C_{K\text{-}40}}{56} \leq 1 \qquad (11b)$$

The denominators are the limiting concentrations, in pCi/g, of each radionuclide when it is the only one present. This relation is analogous to that given by Krisiuk (Kr71a). Various cases with regard to the outside radiation exposure and geometrical configurations that are reflected in equations (4) and (10) need to be considered before selecting the right-hand term in equation (11a). When Ra-226 concentrations are used instead of U-238 concentrations because U-238 is not in the material, almost the same coefficient (1.80) is appropriate.

For limiting internal exposure in terms of WL values, a similar approach with regard to Ra-226 concentrations in construction materials can be applied, utilizing equation (9). For the examples considered in Section 2.4, the Ra-226 limit based on external radiation exposure rates would also be adequate with respect to WL values at normal ventilating rates. Even under conditions of relatively large radon diffusion surface areas per room volume and low ventilation rate (0.5 hr^{-1}), the dose estimates in Section 2.6 indicate that elevation in room air by 0.01 WL requires a Ra-226 source concentration of 12 pCi/g, which is readily detectable by gamma radiation exposure measurements.

The remedial actions recommended for significantly elevated external radiation exposures are reducing occupancy time (or increasing the distance from a localized source), adding shielding, and removing the radioactive material. The choice depends on the feasibility of such action, the magnitude of required dose reduction, and relative costs.

The remedial actions recommended for significantly elevated WL values within a building are increased ventilation with outside air, use of air cleaners to remove Rn-222 daughters, application of a barrier to radon exhalation, and removal of the material that contains the Ra-226 source (Fi76). Reduction of Rn-222 concentrations and additional reductions in WL levels by increasing the rate of air turnover have been demonstrated (Ca75, Wi78, Cl78). If the ventilation rate initially was below normal, order-of-magnitude reductions have been achieved. Equation (9) predicts a simple inverse relationship between Rn-222 concentration and ventilation rate if the latter is much larger than the Rn-222 decay constant. This remedial action is limited by energy conservation and cost considerations where outside air must be heated or cooled.

The usual circulating air heating and cooling systems provide some removal of Rn-222 daughters. The degree of removal can be enhanced with effective air cleaning by filtration or electronic cleaner, and by using relatively high rates (Fi76). Reduction of WL values is limited by the 3-min. half-life of Po-218 (Mo76).

Application of a radon barrier that decreases Rn-222 concentrations within buildings by more than an order of magnitude has also been demonstrated (Cu78). Non-porous coatings applied to walls and floors may reduce the inward flux of Rn-222 from these surfaces. The effect of such barriers must be evaluated over extended periods as fine cracks, pinholes, or penetrations may occur, because coatings have been ineffective whenever the gas had even minor direct pathways. An increase of external gamma radiation exposure rates due to the accumulation of Rn-222 daughters behind the barrier has been noted, but, except under unusual geometric conditions, such increases amount only to 25 percent or less (Cu76, Au76). Whether this small percent increase in the external radiation levels counterbalances a greater than 10-fold decrease in internal exposure rates depends on the radionuclide content of the material.

3. Experimental Study of Survey Methodology

3.1 Objectives

The ongoing and recently completed surveys of radiation in structures cited in Sections 2.3 and 2.4 indicate some difficulties in determining WL elevations due to building materials and in locating by means of a survey those structures that have significantly elevated gamma-ray exposure rates and WL values. This study addresses both difficulties by testing procedures for incorporating in the radiation survey of structures that would determine the radiation dose potential of building materials and predict doses in structures from this dose potential. This approach was developed in the context of a small survey of radiation in structures performed in the Atlanta metropolitan area.

Surveys of WL values and Rn-222 concentrations in structures summarized in Table 2 have shown wide variations geometrically distributed about the mean, but only a few of the elevated values can be unambiguously attributed to Ra-226 in structural material. The most important causes of high WL levels appear to be Rn-222 in outside air, Rn-222 emanation from the ground into the structure, and a low turnover rate for inside air, either separately or in combination. These factors however, generally were not measured in studies and surveys. One approach considered here is determination of the Ra-226 concentrations in building materials to estimate Rn-222 emanation into the structure as a means of distinguishing this source of WL elevation from all others.

Surveys of gamma radiation exposure rates in structures have usually categorized these structures by outside wall material such as wood, brick, or concrete (see Table 1). Specific materials within these categories that cause significantly elevated exposure rates have been identified only in a few instances, such as alum shale used in Swedish concrete. An initial determination of large differences in the radionuclide content of building materials should increase the probability of finding material that may increase significantly the exposure rate in structures. It can also be used to establish sampling subcategories within a material category to differentiate according to the potential for high, medium and low radiation exposure rates. The materials used for foundations, floors, and within structures must also be included in this categorization.

Techniques for determining and using the radiation dose rate potential of building materials were studied in this test survey by the following activities:

1. Test of procedure to categorize radiation exposure potentials of materials with survey meters.
2. Calibration of exposure potential categories by radionuclide analysis of material samples.
3. Test of field gamma-ray spectrometer to determine relative content of Ra-226 (i.e., WL potential) in existing structures where no samples are available for radionuclide analysis.

4. Development of calculational model to relate material exposure potential in terms of radiation exposure index (see Section 2.3) to gamma radiation exposure rate in structure.
5. Application of calculational model to relate Ra-226 content in material to WL value in building air from this source.

Structures were surveyed for gamma radiation exposure rate and Rn-222 concentration, and the survey results were utilized to evaluate these techniques. The observations and the results of the above-listed tests were combined with the information in Section 2 from previous and ongoing surveys to recommend the nationwide survey of radiation in structures presented in Section 4.

The study was undertaken in Atlanta, which was considered a suitable test site with regard to range of structural types, building materials use, and terrestrial radiation exposure, and permitted optimum application of the modest financial resources made available for the study. The distribution between masonry and non-masonry outside wall materials in a sample of one-family dwellings, a major consideration with respect to both gamma radiation exposure rates and WL values, in the Atlanta Standard Metropolitan Statistical Area (1.8 million persons, 15 counties) compares as follows with the national figures in 1975 (Ho76):

	United States	Atlanta SMSA
masonry and masonry on frame	70%	62%
frame without masonry	30%	38%

Care must be taken to compensate for the widespread practice in the Atlanta SMSA to build homes with crawl space (64 percent compared to 32 percent nationally) and the correspondingly fewer homes with basements or on slabs. The relative number of building uses in Atlanta and its immediate vicinity is indicated by statistics on the use of land with buildings from the Fulton County Tax Digest for 1978:

residential	133,800
apartment houses	3,200
commercial	9,700
industrial	300
office and institutional	1,200
government and churches (tax exempt)	6,800
Total	155,000

Fulton County includes most of the city of Atlanta, approximately one-half of the nearby suburbs, and some rural areas; it has approximately one-third of the population of the SMSA and is the most populous county. The statistics appear to be reasonably typical for U.S. cities with regard to the ratio of residential to all structures, but low with regard to industrial relative to commercial, office, and government buildings.

Atlanta lies in the radiation exposure region categorized as "non-coastal" that includes most of the U.S. population (Oa72), but is within 150 km of areas in the "coastal" category. The terrestrial exposure rate given in the compilation of U.S. values by Oakley is, at 7.5 μR/hr (57.2 mrad/yr in air) somewhat higher than the average "non-coastal" value (see Section 2.2). An even higher value, of 10 μR/hr, was given for a single TLD measurement location in Atlanta (Li72). An aerial map of gamma radiation in terms of counts per second (Hi75) shows great variability in the city and its immediate surroundings.

3.2 Procedure

As a first step, building and marketing practices in the Atlanta metropolitan area were considered to determine the use pattern of various construction materials and identify suppliers of these materials, their sources and their constituents. Inquiries were made of builders' and material suppliers' trade associations to assure that local findings of trade practices were applicable nationally. Emphasis was placed on masonry, defined here broadly to include stone, concrete, stucco and brick, because it had been consistently identified as responsible for elevated interior exposure rates and Rn-222 concentrations in air. This information was collected so that the most widely used materials and those that were expected to cause the highest exposures could be surveyed for their radiation exposure potential in structures built currently, recently, and in the immediate future. Historical information for evaluation of past practices was also collected, but was found to be of questionable reliability because material suppliers changed frequently. The most useful information was obtained through the local branch of the National Association of Home Builders and from individual suppliers of poured concrete, concrete blocks, bricks, and general building materials.

At supply yards, the materials were examined for radionuclides that emit gamma rays with a survey meter that consisted of a cylindrical 5x5-cm NaI(Tl) detector with count-rate meter, adjusted to measure gamma rays above 90 keV. The detector was centered on large piles of materials for brief 0.1- or 1-min count-rate measurements to indicate whether the material was in an exposure rate category considered medium (similar to ambient levels) or significantly higher or lower. The materials included most types of building materials, especially brick, decorative tile, concrete block, and their major constituents. To calibrate this survey procedure, representative samples at medium radiation levels and samples of all materials at significantly higher or lower levels were analyzed in the laboratory for radionuclide content. Samples of materials used in older structures were also analyzed when available.

The samples were placed in cylindrical 500-cc containers, weighed, and analyzed for photon-emitting radionuclides with a heavily shielded Ge(Li) detector and 4,000-channel spectrometer. The laboratory counting period was usually 10,000 seconds. The following radionuclides were measured by the indicated gamma rays, with the percent gamma ray per disintegration given in parentheses (Ko77):

Ra-226	186 keV (3.3%)		
Pb-214	295 keV (19%);	352 keV (37%)	
Bi-214	609 keV (46%);	1,120 keV (15%);	1,764 keV (16%)
Ac-228	338 keV (11%);	911 keV (28%)	
Tl-208	583 keV (30.8%);	2,615 keV (35.9%)	
K-40	1,461 keV (10.7%)		

The disintegration rates of the two Pb-214 and three Bi-214 gamma rays were used to determine the equilibrium activity of Ra-226. These two radionuclides emit all of the gamma rays among the short-lived Ra-226 progeny and contribute most of the exposure rate due to gamma rays from the U-238 chain. The measurement at 186 keV includes a gamma ray from U-235 (54%), hence, this measurement can be used only if the ratio of Ra-226 to U-235 is known. If U-238 is in equilibrium with Ra-226 and is at its natural isotopic ratio, then U-235 contributes 2.5% per disintegration, and the total gamma-ray fraction for U-235 plus Ra-226 is 5.8%. The disintegration rates of the two Ac-228 and Tl-208 gamma rays were taken to represent the activity of the Th-232 progeny if the two radionuclides were equal.

The detector system had been calibrated for counting efficiency with NBS radioactivity solution standards. Minor correction factors for gamma-ray attenuation within the sample were applied when sample densities were between 1.0 and 1.8 g/cc. Small samples were counted in the form obtained, and larger samples such as bricks, tiles, blocks and poured concrete were broken into smaller pieces.

The external gamma-ray exposure potentials of the materials were characterized relative to their measured radionuclide concentrations in terms of the exposure rate index discussed in Section 2.3 and the factors in equation (1):

$$\dot{I} = 1.82\ C_{U-238} + 2.82\ C_{Th-232} + 0.179\ C_{K-40} \qquad (12)$$

By this calculation, contributions from the several radionuclides could be weighted appropriately for the exposure conditions normally encountered. Values of I would be expected to reflect within a few μR/hr the exposure rate from the material within the structure, as discussed in Section 2.3.

External gamma radiation exposure rates were measured within and outside approximately 60 buildings in the Atlanta area. Many of these were homes that were surveyed during construction in order to relate exposure rate changes to the analyzed materials that were used. The other structures had been built between 1911 and 1976. The homes under construction were in four subdivisions that had been selected to cover the range of costs from modest to expensive (locations A to D, respectively). When unusually high radiation exposure rates were measured, the radiations were traced to the construction material that was the source, and efforts were made to identify the responsible constituent and its origin.

Radiation exposure rates outside and inside houses were measured 1 m above the ground or floor with a pressurized ionization chamber (PIC). The PIC had been calibrated in terms of μR/hr with a Ra-226 standard checked by NBS before use. At least 20 consecutive readings were averaged at each location to obtain standard deviations between 0.3 and 0.8 μR/hr. Outside radiation exposure rates were determined around the house at sufficient distance to minimize radiation exposure from house walls and at locations that appeared to define the range of nearby outside levels. Some surface soil was collected and analyzed for radionuclide content to compare the exposure rate computed by equation (1) with direct measurements. Outside exposure rates were also compared to gamma-ray count-rate isopleths mapped by aerial survey in 1959 (Hi75).

Radiation exposure rates within houses were measured in various rooms on each floor. The PIC was placed at the center of rooms, at off-center locations considered to represent the room with regard to exposure rates, and next to possible radiation sources such as walls, floors, and fireplaces to observe the extent of exposure rate variation and identify the major contributors to the radiation exposure.

To obtain more rapid measurements, the cylindrical 5x5-cm NaI(Tl) detector with count rate meter was calibrated relative to the PIC over a range of terrestrial exposure rates from 2 to 40 μR/hr. Survey-meter readings, $\dot{S}$, in kilocount/min, varied approximately linearly with exposure rate, $\dot{R}$, in μR/hr, according to the relation

$$\dot{R} = 1.6\,\dot{S} + 3.9 \tag{13}$$

The value of the last term suggests that the NaI(Tl) survey meter detects almost no cosmic rays, only terrestrial radiation. Because the counting efficiency of this detector decreases sharply with gamma-ray energy, the above calibration is affected by the relative intensities of the terrestrial radionuclides. The survey meter was, therefore, used in conjunction with the PIC to delineate exposure rate patterns and obtain approximate values.

The NaI(Tl) survey meter with a single channel analyzer and two mobile Ge(Li) detectors, one 85-cc and the other 55-cc in volume with multi-channel analyzers, were tested in buildings that showed elevated external radiation rates to determine whether the instruments could identify the terrestrial radionuclide that caused these increases. High concentrations of Ra-226 but not of Th-232 daughters or K-40 could cause elevated internal radiation exposure from Rn-222 daughter products. Although spectra obtained with both types of detectors could be used to distinguish the three sets of gamma rays, the Ge(Li) spectrometer was so much more effective in measuring relative intensities that it was used in all subsequent determinations.

For this analysis, the photoelectric peaks of gamma rays at 352, 609, and 1,764 keV emitted by Ra-226 daughters were used to calibrate the Ge(Li) detector for counting efficiency. Relative counting efficiencies for Th-232 chain gamma rays at 583 and 911 keV, and for K-40 at 1,461 keV were found by interpolating from these values. The relative concentrations of the Ra-226 chain, the Th-232 chain, and K-40 were estimated by applying these relative counting efficiencies and the gamma-ray fractions to the count rates under the characteristic gamma-ray peaks.

To measure Rn-222 concentrations in buildings, a passive battery-operated radon-daughter collector with TLD detector (Ge77) was used. The TLD is mounted on a collector electrode at a 900-volt potential at the narrow end of a funnel into which air moves by natural circulation through a grid and a desiccating medium. A second TLD in the monitor, located distant from the electrode, is used to determine the gamma-ray background for subtraction. One of the monitors was calibrated by the U.S. DOE Environmental Measurements Laboratory to have a sensitivity of 21.8 pCi-hr/liter per dosimeter mR unit reading; the sensitivity for a smaller monitor was determined to be 10.4 pCi-hr/liter per dosimeter scale unit by comparison to this calibrated one.

Exposure rates within a building due to terrestrial radionuclides in building materials were calculated both by hand and with a computer program. The former determined the exposure rate at a single location from sources both outside and in several types of walls and floors. The latter determined exposure rates from concrete floor and brick walls at grid points within structures of variable dimensions.

For the hand calculation, the exposure rate within the house was considered to be the sum of the exposure rates from attenuated cosmic rays, from radionuclides in soil as attenuated by house walls (but not windows) and floor, and from radionuclides in the walls and floor. The radiation exposure rate from terrestrial radiation is the measured outside value, multiplied by the fraction of the total in the angle from the vertical subtended at the test point by wall or floor, and also multiplied by the fraction transmitted by wall or floor. The radiation exposure rates from walls and floor are the $\dot{I}$ values for the material, multiplied by the fraction of the exposure rate from the angle subtended by walls and floor and the fraction from the actual thickness of material. The fractional exposure rate as a function of angle was read from a figure given by Beck (Be72) and was averaged for the geometrical configuration of walls and floor relative to the exposure point. Thus,

$$\dot{X}_i = \text{attenuated cosmic ray exposure rate + attenuated terrestrial exposure rate + exposure rate from wall and floor materials} \qquad (14)$$

$$\dot{X}_i = c\dot{X}_c + (\dot{X}_a - \dot{X}_c)\,[\,a_f b_f + (1-k)\,(1-a_f) + k(1-a_f)\,b_w\,] + a_f(1-b_f)\dot{I}_{(f)} + ka_w(1-b_w)\dot{I}_{(w)}$$

where $\dot{X}_i$ = exposure rate in house, μR/hr

$\dot{X}_c$ = cosmic ray exposure rate, μR/hr

$\dot{X}_a$ = outside exposure rate, μR/hr

a = fraction of exposure rate in angle subtended relative to exposure rate from infinite medium

b = fractional transmission of gamma rays by building material

c = fractional transmission of cosmic rays by building materials

k = fraction of wall surface not windows

f,w = floor and walls, respectively

For a sample calculation, surface densities of 4, 17, and 23 g/cm^2 were used for wooden frame wall, brick veneer wall, and concrete slab construction, respectively. No consideration was given to radiation sources and attenuation within the building; 90 percent transmission (c=0.9) of cosmic rays by roofing was assumed (NC75). The building was considered to be a 1-floor plan, 9.0 m x 17.6 m x 2.4 m, with windows occupying 15 percent of the wall space (k=0.85). The point of exposure was taken to be on the long center line, 3 m from one end wall and 1 m above the floor. Exp (-μx) was used for the fractional transmission, b, where μ is the mass attenuation coefficient and x the material surface density. An attenuation coefficient for 1.0 MeV gamma rays of 0.064 cm^2/g was applied.

The computer calculation was by the modified code FUDGE 4 (Ma64) and is given in Appendix A. The values of μR/hr at a grid of locations within a room for the three terrestrial radionuclides in walls and floor unit concentrations were obtained for square structures, 2.4 m high, with various floor areas between 100 and 1,600 m^2. Wall and floor surface densities were 17 and 23 g/cm^2, respectively. The values are approximate because only mean values of gamma-ray energies and fractions were used for the two decay chains (U-238: 0.81 MeV, 210%; Th-232: 0.88 MeV, 270%; K-40: 1.46 MeV, 10.7%). Results depend noticeably on the choice of buildup factors, for which Taylor's sum of exponentials was used (Mo73).

3.3 Results

Production of ready-mix concrete and the manufacture of concrete block are concentrated in the Atlanta area. Two major producers plus one smaller company provide the bulk of the concrete used locally. The concrete varies in strength but is generally the lightweight type, as contrasted to heavier types used as recently as ten years ago. Samples were obtained from all three producers.

Concrete blocks and ready-mixed concrete are prepared from a mixture of cement, fine aggregate and coarse aggregate, conventionally in the ratio 1:2:4, with water. As the demand for stronger and lighter concretes has been rising, producers have been experimenting with other ratios and with various substitutes for the traditional materials. For example, grindings or rock dust may be used as part of the fine aggregate, and as much as 20% of the cement material may be fuel ash rather than portland cement. Phosphate slag formed into a fine light sand by a producer in northern Alabama was used as aggregate until shipments were terminated. Expanded shales and exploded clays are increasing in use as coarse aggregate to lower the weight. Of these constituents, gravel and rock dust are obtained nearby, sand is from Georgia and nearby Alabama and South Carolina, and ash and cement can be either of local or distant origin.

Clay bricks are commonly used in the Atlanta area as veneer on homes and commercial buildings in conjunction with wood frame or concrete blocks. Samples were obtained from 6 of 7 brick companies operating in Georgia. In addition, samples of bricks from adjacent states, but stocked for use in Atlanta, were obtained. Included were bricks from South Carolina, North Carolina, Virginia and Tennessee, plus one lot from Ohio. Georgia bricks were from clay at Atlanta, Augusta, Macon and Columbus. In most cases, the user orders bricks by color and type, and delivery is made directly by the producer. Popular styles and colors are stocked in Atlanta and were available for sampling and analysis.

The survey of construction materials with a NaI(Tl) detector at the suppliers' yards suggested the five exposure rate categories given in Table 4. Count rates ranged from 1,500 to 6,000 count/min. in the environment and to 12,000 count/min. over building material. The categories were usually in clearly differentiated narrow count-rate ranges. The medium category has count rates near the upper end of the range of the natural background and is by far the most common for brick, concrete, and concrete block. The bricks in the 'high' category were mostly of local origin; those in the 'low' category were mostly from South Carolina. The bricks that yielded very low count rates are used only for special decorative purposes; one type was made of lime and sand, the other of marble chips. The two concrete blocks that showed very high readings are not in current use but were obtained from older buildings in which elevated exposure rates had been measured.

The content of radium-226 daughters and thorium-232 daughters in the medium-category bricks was approximately 1 to 3 pCi/g each, and that of potassium-40 was 10 to 30 pCi/g. In the medium-category concrete and concrete blocks, the concentrations of Ra-226 and Th-232 daughters were at the lower end of this range, while the concentration of K-40 was at the upper end. These concentrations are of the same magnitude as reported for materials elsewhere (Ha71, Kr71, Ko78a). Measured values of the Ac-228 and Tl-208 concentrations were identical within the uncertainty of measurement, suggesting that the radioactive decay series beginning with Ra-228 was in equilibrium. The concentrations of Pb-214 and Bi-214 also were equal; in 31 brick and 14 concrete slab and block samples they averaged, respectively, 98 ± 12 (1σ) and 91 ± 10 (1σ)

Table 4

Radionuclide Content of Exterior Wall
Construction Materials

Material	Exposure Rate Category	No. of Samples	^{226}Ra daughters (^{214}Pb, ^{214}Bi), pCi/g	^{232}Th daughters (^{228}Ac, ^{208}Tl), pCi/g	^{40}K, pCi/g	Exposure Rate Index, μR/hr
Brick	very low	2	0.2 (0.1-0.3)	0.08 (0.04-0.1)	0.3 (0.2-0.4)	0.7 (0.6-0.7)
	low	5	0.6 (0.6-0.7)	0.9 (0.8-1.0)	12. (11-13)	5.8 (5.3-6.4)
	medium	24	1.8 (1.0-3.4)	1.9 (1.1-3.0)	17. (10-28)	12. (9.4-16)
	high	6	3.5 (2.8-4.8)	2.9 (2.4-3.9)	27. (21-32)	20. (17-22)
Concrete	low	3	0.7 (0.5-1.1)	0.5 (0.4-0.6)	8.0 (7.1-9.8)	4.1 (3.3-5.4)
	medium	6	1.5 (1.0-1.8)	1.7 (1.3-1.9)	26. (18-31)	12. (8.7-14)
	high	1	2.4	3.2	27.	18.
Concrete block	medium	8	1.3 (1.1-1.6)	1.7 (1.2-2.2)	26. (24-31)	12. (10-14)
	very high	2	21.	1.0	8.6 (7.7-9.4)	43. (42-43)

Notes: 1. Values are averages, with extremes in parentheses.

2. Concentrations of individual samples were computed for ^{226}Ra daughters by averaging 5 gamma-ray values for ^{214}Pb and ^{214}Bi, and for ^{232}Th daughters, by averaging 4 gamma-ray values for ^{228}Ac and ^{208}Tl.

percent of the equilibrium value relative to the concentration of Ra-226, based on the summed 186 keV gamma-rays of Ra-226 and U-235.

The exposure rate indices (see Table 4) computed from radionuclide concentrations were consistent with the categories utilized in surveying the construction materials. The medium category for the three materials each showed an average index of 12 μR/hr, which is at the high end of the range of terrestrial radiation background (see below). The index, therefore, appears to fulfill its main function: to describe the combined radiation exposure rate from three sets of radionuclides of variable concentrations as a value that can be related to the terrestrial background. Because the index is the exposure rate from an infinite hemisphere, it can be reasonably applied for surveying large piles of construction materials. The possibility of radionuclides in the chain from U-238 to Ra-226 not being at equilibrium values relative to Ra-226 does not significantly affect the index because of the relatively small gamma-ray exposure rate from the radionuclides preceding Ra-226.

Other construction materials that were surveyed in large quantities with the NaI(Tl) detector and did not show any significantly elevated exposure rates are summarized in Table 5. The values are tabulated as the fraction relative to ambient levels of count rates observed with the detector above them. Values between 0.8 and 1.3 of ambient are considered to be in the medium exposure rate category, and those between 0.2 and 0.8, in the low category.

Samples of tile, monazite byproduct, and wood ash that were analyzed had the radionuclide levels given in Table 6. The wood sample contained so little activity that it could only be analyzed after concentration by ashing. Exposure rates from the tiles would normally be less than indicated by the index because they are relatively thin. The zircon byproduct from processing monazite sand for thorium production in Georgia is not used in ordinary construction, but for making refractory products.

The same exposure rate categories observed for brick and concrete also applied to the clay used in brick and the concrete constituents shown in Table 7. All items except phosphate slag and fly ash were obtained locally, either from active supply piles at concrete suppliers or at a local clay pit for brick manufacture. No clays for bricks produced elsewhere are included. The constituents in the medium and low exposure rate categories thus can account for the local brick and concrete at these levels, although the medium categories of gravel and rock dust, which are usually from the same local granite quarries, have lower exposure rate indices than expected -- i.e., approximately 9 rather than 12 μR/hr.

Visits to some of these local sources -- a clay pit, a granite quarry, and Stone Mountain, a large expanse of granite -- confirmed the magnitudes of the exposure rate indices. External exposure rates (including cosmic radiation) measured at the three locations were:

> clay pits -- 15 and 30 μR/hr at the sources of the medium and high clay, respectively;

Table 5

Relative Exposure Rate of Common Building Materials

0.2 - 0.8 of ambient

- gypsum wall board
- gypsum insulation sheathing
- gypsum ceiling tiles
- plywood insulation sheathing
- roll roofing material
- foil-backed fiber glass roll insulation
- hard-board siding
- wood (5 varieties)
- concrete mixes (sand, mortar)
- cements (portland, masonry)
- styrofoam insulation board
- particle board
- galvanized steel wall braces
- window glass (single and double)
- sand
- river stone gravel

0.8 - 1.0 of ambient

- fire brick
- concrete mix
- glass fiber roll insulation

1.0 - 1.3 of ambient

- concrete block
- terra cotta flue liner
- granite gravel

Note: Measured by placing NaI(Tl) survey meter on large pile of material. Typical ambient exposure rate was 10 μR/hr (including cosmic radiation).

Table 6

Radionuclide Content of Some Materials used in Structures

Material	Exposure Rate Category	No. of Samples	^{226}Ra daughters (^{214}Pb, ^{214}Bi), pCi/g	^{232}Th daughters (^{228}Ac, ^{208}Tl), pCi/g	^{40}K, pCi/g	Exposure Rate Index, μR/hr
Tiles	low	9	1.9 (1.6-2.2)	1.0 (0.7-1.3)	5.3 (2.3-21)	7.2 (6.0-8.6)
	medium	1	1.7	2.1	28.	14.
Wood	very low	1	0.04	0.013	0.3	0.16
Zircon	very high	2	69. (59-79)	12. (8.8-14)	1.4 (1.1-1.7)	160.

Notes: 1. Tiles are decorative clay wall and floor tiles

2. Wood from mixed sources analyzed as 2.2-percent ash

3. Zircon is byproduct from monazite mining used in refractory materials.

Table 7

Radionuclide Content of Concrete Components and Clay for Brick

Building Material Constituents	Exposure Rate Category	No. of Samples	^{226}Ra Daughters (^{214}Pb, ^{214}Bi), pCi/g	^{232}Th Daughters (^{228}Ac, ^{208}Tl), pCi/g	^{40}K, pCi/g	Exposure Rate Index, μR/hr
	Coarse aggregate					
Gravel	low	3	0.3 (0.2-0.4)	0.3 (0.06-0.6)	6.2 (1.5-8.6)	2.5 (1.2-3.6)
(granite)	medium	5	0.9 (0.6-1.5)	1.2 (1.0-1.7)	22. (15-30)	9.1 (6.6-13)
Shale/clay	medium	6	1.2 (0.9-1.6)	1.6 (1.3-2.1)	23. (16-34)	11. (8.8-12)
	high	4	2.1 (1.9-2.3)	3.4 (2.9-4.0)	25. (22-29)	18. (16-19)
	Fine aggregate					
Sand	low	5	0.3 (0.1-0.6)	0.4 (0.2-0.6)	3.2 (1.1-5.6)	2.4 (1.4-3.0)
Rock dust	low	1	0.4	0.4	8.8	3.4
	medium	3	1.2 (0.7-1.9)	1.3 (0.8-2.0)	21. (14-33)	9.6 (6.0-15)
Phosphate slag	very high	5	28. (19-38)	0.8 (0.6-0.8)	4.2 (1.9-5.7)	57. (36-73)
	Cement					
Cement	low	6	1.0 (0.5-1.4)	0.3 (0.2-0.6)	2.1 (0.7-2.9)	3.3 (1.6-5.9)
Fly ash	medium	2	3.4 (3.3-3.5)	2.4 (2.0-2.8)	8.2 (3.3-13)	14. (14-15)
	high	14	5.3 (3.5-8.3)	3.1 (2.2-4.3)	19. (4-28)	22. (16-29)

granite quarry -- 16 µR/hr
north face of Stone Mountain -- 15 µR/hr.

The count rates obtained by the aerial survey at the clay pit and Stone Mountain locations are 750-875 count/sec; the quarry is not in the surveyed area.

The contribution of radionuclides in ash to the radiation exposure would not be significant even for the highest ash exposure rate index reported in Table 7 because only a small fraction of concrete is ash. An index of 29 µR/hr in the 3 percent of the concrete that may be ash adds less than 1 µR/hr to the mixture.

The phosphate slag was obtained in seeking the source of the significantly elevated exposure rate indices for the two concrete blocks listed in Table 4. A geologist who examined the two blocks suggested that the one common component was expanded slag from the thermal phosphorus production process. The producer of this material, located approximately 320 km from Atlanta, provided information that 378,000 tons had been shipped to two Atlanta concrete manufacturers in the years 1962 - 1968 (Ma78). An additional 87,000 tons was sold to 30 other companies in Georgia, of which 4 companies in Thomasville, Albany, Americus, and East Ellijay obtained 67,000 tons (Ma78). The producer also supplied the samples for which analytical results are presented in Table 7.

The Ra-226 content of the phosphate slag samples is consistent with the concentration in the mixed ore, as discussed in Section 2.5. At a slag content of 80 percent the blocks would have an average Ra-226 concentration of 22 pCi/g, compared to the measured value of 21 pCi/g given in Table 4.

The radiation exposure rate in the Atlanta area outside homes was observed to range from 6 to 14 µR/hr. The terrestrial component is lower by the amount contributed by cosmic rays, which at the 300-m altitude of Atlanta was estimated as 3.8 µR/hr. This value was calculated from a curve of dose rate in air vs. elevation (NCRP, 1975) and was also used by Lindeken et al. (1972). Average exposure rates differed significantly among locations, but were usually within the standard deviation range at a particular location. Measurements repeated at specific locations after intervals of several months in some cases were identical, but in others differed by as much as 2 µR/hr. Seasonal variations of this magnitude have been observed previously (Li73, Ni78). Such changes are attributed to the accumulation and release of Rn-222 and its daughters just below the surface of the ground in response to ground moisture and atmospheric pressure changes, and in ground-level air in response to atmospheric stability changes.

The measured terrestrial exposure rates of 2 to 10 µR/hr are consistent with the values of 1.6 to 12 µR/hr calculated from samples of surface soil taken at several Atlanta metropolitan area locations, as summarized in Table 8. The range of Ra-226 daughter to Ra-226 ratios, from approximately 0.6 to 1.2, when allowing for uncertainty of approximately ±0.1 pCi/g for each measurement, suggests the potential for variation in the exposure rate due to the varying retention of short-lived Ra-226 daughters in soil. These calculated exposure

Table 8

Terrestrial Radionuclide Concentrations in Atlanta Area Surface Soil

Location	Radionuclide concentration, pCi/g				Calculated terrestrial radiation exposure rate,** μR/hr
	Ra-226*	Ra-226 daughters	Ra-228 daughters	K-40	
Central Atlanta	0.8	1.0	1.1	17	8.0
	1.8	1.3	1.2	16	8.6
	2.6	2.0	1.5	20	12
	1.4	1.3	1.1	18	8.7
North Atlanta	0.5	0.4	0.3	1.7	1.9
	0.4	0.3	0.3	0.9	1.6
	0.4	0.3	0.4	1.8	2.0
	0.5	0.3	0.4	5.8	2.7
Marietta (NW)	1.6	1.4	1.9	11	9.9
	1.5	1.2	1.6	16	9.6
	0.5	0.4	0.7	2.0	3.1
	0.4	0.5	0.8	2.4	3.6
Decatur (E)	1.1	0.9	1.1	4.1	5.5
East Point (S)	1.1	1.0	1.1	5.0	5.8
	2.4	2.1	2.2	4.8	11
Newnan (SW)	0.7	0.5	0.4	3.6	2.7

---

* Ra-226 concentration is based on the assumption that the characteristic 186-keV gamma ray used for detection is 57 percent from Ra-226 and 43 percent from U-235.

** This value is based on Ra-226 (U-238) daughter, Ra-228 (Th-232) daughter and K-40 concentrations according to equation (1).

rates are approximate because they are based on only a small sample of the terrestrial source term. The aerial survey values shown in Figure 1 that range, except for some isolated high values, from 250 to 1250 counts/sec in the Atlanta metropolitan area, are also consistent with a five-fold range of external terrestrial exposure rates.

The observed exposure rates within homes in Atlanta (see Table 9) qualitatively have the same relation to outside rates as reported earlier: exposure rates in wood-frame houses are lower than outside and in homes built with concrete and brick are higher. They confirm that frame-house construction materials attenuate the gamma radiation from the soil outside while contributing almost no radiation, while concrete and brick act both as radiation shield and source. The source effect is especially noticeable at location B, where concrete with a higher radiation exposure index used in three of eight homes led to higher exposure rates. At location D also, the stone used for exterior facing and in the fireplace noticeably elevated the measurements performed nearby.

The influence of walls and floors as source and shielding material can be seen in the changed exposure rates measured during construction, shown for a typical home in Table 10. Concrete floors and walls add noticeably to the radiation exposure rate that had existed prior to construction at that location, but this effect decreases in upper stories where walls and floors are wooden.

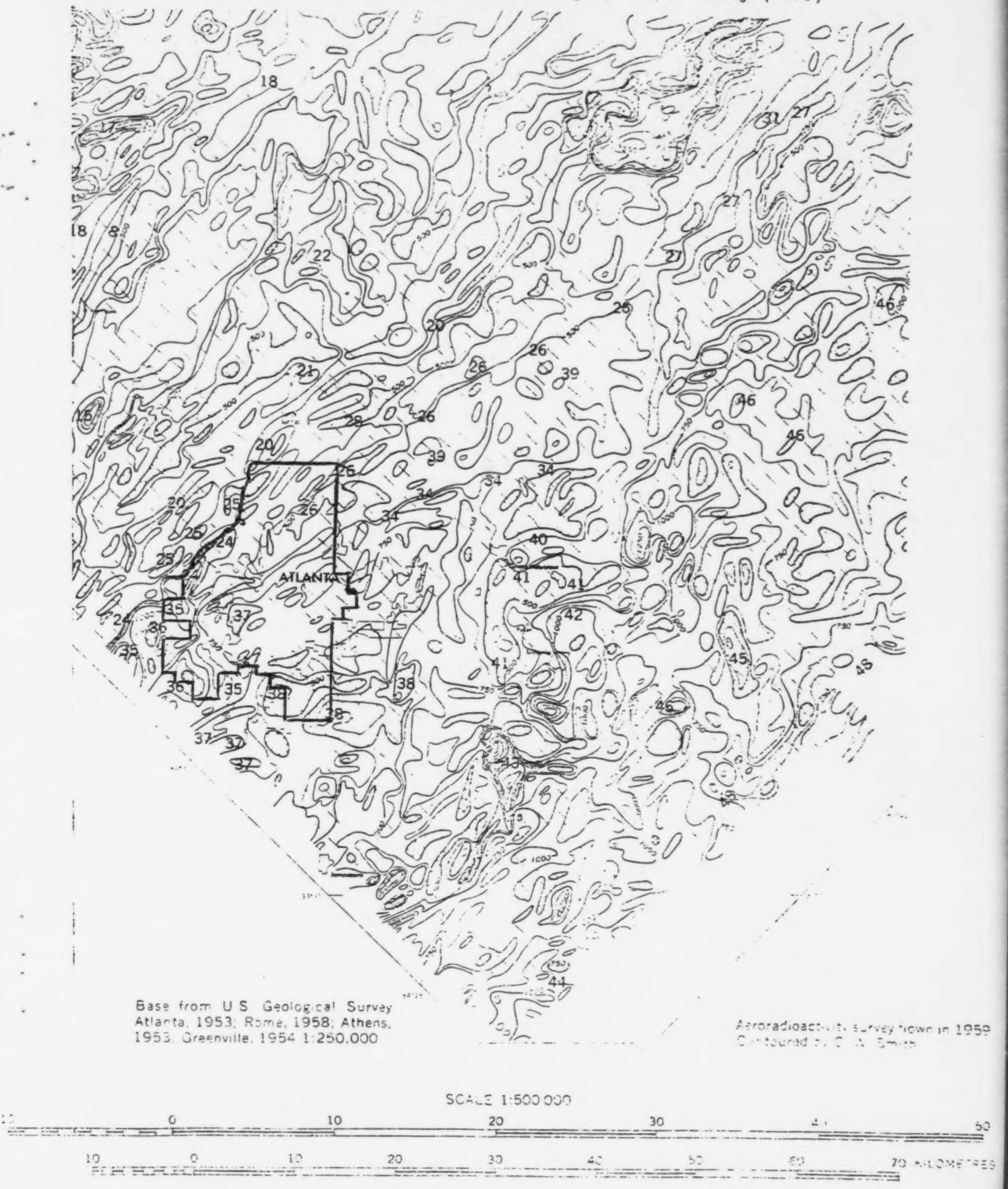
The exposure rates measured in apartment houses, commercial-industrial buildings, and schools, compiled in Table 11 are, with significant exceptions, similar to the exposure rates outside, ranging from 40 percent higher to 40 percent lower. In the multi-story poured-concrete office structure, the exposure rates were within 2 µR/hr on each of the five stories, and the only elevated readings were from concrete blocks in stairwells. Even exposure rates in buildings constructed with local granite blocks were on the average only 4 µR/hr higher inside than outside, and no higher than many other buildings.

Significantly elevated radiation exposure levels were encountered at three locations due to concrete block and at one due to glazed brick. The glazed brick is probably from clay in the high exposure category (see Table 7), and the concrete blocks are believed to contain the phosphate slag listed in Table 7. These blocks were used in three of the school buildings for some of the inside walls. At the airport, where concrete blocks are used extensively, only four sections of wall,each several meters long,were found with elevated levels: one on the passenger concourse, two in the terminal basement, and one at a warehouse. One wall at one of three warehouses in the suburban Atlanta area also contained these blocks.

Within these structures, sources of radiation were readily detected by the increase in exposure rates upon approach. As shown in Table 12, exposure rates increased when moving over a relatively non-radioactive floor toward a more radioactive wall, or when moving from relatively non-radioactive walls toward the center of a more radioactive floor. Within multi-story homes, the

Figure 1

Aeroradioactivity Map of Atlanta, Georgia, and Vicinity (Hi75)


ATLANTA
18
22
20
21
28
26
25
39
34
40
41
42
38
37
36
35
24
27
31
46
45
44
500
750
1000
SCALE 1:500 000
0
10
20
30
50
70 KILOMETRES

Base from U S Geological Survey Atlanta, 1953; Rome, 1958; Athens, 1953; Greenville, 1954 1:250,000

Aeroradioactivity survey flown in 1959
Contoured by C. A. Smith

Table 9

Exposure Rates in 1-Family Homes

Location	House style	No. of houses	Average exposure rate (and range), µR/hr			
			Outside	Inside typical	Inside low	Inside high
New homes						
A	1-floor partial brick veneer, concrete wall base, wooden floor	1	8.6 (7.4-9.7)	9.3	8.4	9.9
	1-floor partial brick veneer concrete slab	4		11.	10. (9.6-12.)	12. (11-13)
	split-level frame, concrete slab at lowest level	2		14* 9.6	8.6 (8.1-9.1)	16. (16-16)
B	1-floor frame concrete slab	2	6.8 (6.3-7.6)	7.1	7.0 (6.7-7.2)	7.2 (6.8-7.6)
	split-level frame, concrete slab at lowest level	3		7.5	6.8 (6.7-6.9)	7.9 (7.5-8.1)
		1		14* 8.5	8.3	18
	2-story frame, concrete slab and block-wall basement	2		15** 9.1	8.8 (8.6-8.4)	15. (14-16)
C	2-story brick veneer, concrete slab and block-wall basement	6	11. (10-11)	14.	8.6 (8.0-10)	14. (11-15)
D	3-story brick veneer, concrete slab and block-wall basement	1	12.	14.	12.	16.
	2-story wood and stone exterior	1	9.5	11.	12.	19.
Older homes						
E	1-floor wood frame, pillar foundation (1938)	1	9.7	8.3	8.0	8.8
F	1-floor wood frame, brick facing (1955)	3	9.6 (9.6-9.7)	10.	9.3 (9.0-9.8)	12. (11-13)

Location	House style	No. of houses	Average exposure rate (and range), µR/hr Outside	Inside typical	Inside low	Inside high
G	2-story brick veneer, concrete slab basement	1	9.7	16.† 11. 8.	8.1	18.
S	2-story wood, concrete wall and slab basement	1	6.5	9.4	6.9	17.

---

* first value is lower level, second value is upper level

** first value is first floor, second value is second floor

† basement, first floor and second floor, respectively

Notes: 1. exposure rates include cosmic ray value (3.8 µR/hr outside)
2. ranges refer to different homes

Table 10

Changes in Terrestrial Radiation Exposure
Rates During Home Construction

Measurement occasion	Terrestrial Exposure Rate, μR/hr Basement	Main floor	Second floor	Exposure Rate Index, μR/hr
pre-construction	2.7	--	--	2.1 (1.6-2.7) in soil
concrete walls (3) erected in basement	5.3	--	--	12 (12-13) in concrete
concrete basement slab, outside house walls completed	9.0	5.5	3.1	

Notes: 1. measurements were performed at center of 11m x 7m home S

2. basement has concrete walls on long and two short sides, 2.4m high; remainder of house is wood frame

Table 11

Exposure Rates in Apartment, Commercial and Educational Buildings

Location	Type	Style	No. of buildings	Exposure rate, μR/hr Outside	 Inside typical	 Inside high
GIT	school (3-story)	concrete block	5	13 (11-14)	11 (8.8-12)	31 (19-46)
		glazed brick	2		8.3 (6.3-10)	21
		concrete/ brick facing/ glass	4		13 (11.7-14)	----
		brick	2		9.0 (8.6-9.5)	----
Oglethorpe (1915-1941)	school (3-story)	granite block	4	9.5	13 (10-15)	
U.S. EPA (1976)	office (5-story)	concrete	1	13	13 (12-14)	14.
North Ave	Apartment (8-story)	brick veneer	1	11	15 (14-18)	----
	Public Bldg. (2-story, 1911)	brick	1	11	13	----
	Apartment (2-story)	brick facing/ frame	2	9.0	8.9 (8.0-10)	----
Airport	Warehouses (1966)	concrete block/metal	3	12 (10-16)	11 (8.5-14)	43 (42-43)
	Passenger terminal (1970)	concrete block	1	11	13 (9.0-16)	26 (22-29)
Doraville - Norcross	Warehouses	concrete block wall/concrete floor	3	10	14 (12-16)	37

Note: Exposure rates include cosmic ray value (3.8 μR/hr outside)

Table 12

Exposure Rates in Structures as Function of Measurement Location

Floor material	Wall material	Terrestrial Exposure Rate, μR/hr at wall	Terrestrial Exposure Rate, μR/hr in center
basement of home under construction			
soil	concrete	12	5.3
concrete	concrete block	12	5.9
1-family homes			
concrete	stone	8.8	11
concrete	wood	7.5	9.5
wood	sheet rock	4.2	4.6
wood	brick	6.0	4.7
wood	concrete block	11	10
school room			
concrete	concrete block with phosphate slag	30 33 40	23

Notes:
1. cosmic ray component was subtracted from measurement
2. measurement was performed within room 1 m above the floor in center of room and against outside wall except in school room, where all walls were inside building
3. in school room, first value at wall is in center of long side (7½ m), second value is in center of short side (6 m), and third is in corner

highest radiation exposure rates were at the lowest story directly over the concrete slab, and particularly in basements with concrete walls and floor, and decreased toward the upper stories. The changes in the values shown in Table 10 for home S are particularly large because the basement walls are 15 cm thick rather than the more usual 10 cm, and are constructed of concrete in the medium rather than low exposure rate category. The low exposure rates per home in Table 9 usually reflect measurements at the center of the room in upper stories, while high values were obtained near walls and floor at ground level or in the basement.

Use of inside-to-outside ratios of 0.70 relative to the terrestrial background for frame houses and 1.3 for masonry houses recommended by Moeller and Underhill (Mo76) predicts the median inside non-cosmic-ray exposure rate (i.e., the measured value minus 0.9 x 3.8 μR/hr) reasonably well for most of these homes. Frame houses with concrete slabs must be considered in the masonry category for this purpose. The generally higher values in basements and lower exposure rates in upper stories are also consistent with the factor of 1.3 for basements relative to the outside and the additional factor of 0.85 for upper stories used by Moeller and Underhill. The obvious exceptions are in the use of concrete with higher radionuclide content at home locations B and S, and of stone at location D.

The influence of various levels of radioactivity in building materials is taken into account by the calculational model in terms of the exposure rate index. Sample calculations based on equation (14) result in the following equations for a 1-floor house of the dimensions specified in Section 3.2:

wood frame--
$$\dot{X}_i = 0.9\,\dot{X}_c + 0.8\,(\dot{X}_a-\dot{X}_c) \qquad (15a)$$

frame with concrete slab--
$$\dot{X}_i = 0.9\,\dot{X}_c + 0.4\,(\dot{X}_a-\dot{X}_c) + 0.6\,\dot{I}_{(f)} \qquad (15b)$$

brick veneer with concrete slab--
$$\dot{X}_i = 0.9\,\dot{X}_c + 0.3\,(\dot{X}_a-\dot{X}_c) + 0.6\,\dot{I}_{(f)} + 0.2\,\dot{I}_{(w)} \qquad (15c)$$

Accordingly, the non-cosmic-ray exposure rate is 80 percent of the outside value in a frame house; if the radiation exposure index of building materials is the same as the terrestrial exposure, then the non-cosmic-ray exposure rate would be the same inside and outside a frame house with concrete slab, and 10 percent higher within a concrete slab/brick veneer house.

The above equations are more detailed versions of the approximation in equation (4). The computed values are within the range of the measurements in Table 7. For example, the inside exposure rate in the frame house with wooden walls at location E was computed to be 8.1 μR/hr, and the concrete-slab houses at location A, 12.5 μR/hr if the concrete has a radiation exposure index of 12 μR/hr. At location B, the computed radiation exposure rate in a concrete-slab house is 7.1 μR/hr if the concrete exposure rate index is 4.1 μR/hr, and 11.8 μR/hr if the index is 12 μR/hr. If both concrete slab and brick walls have an index of 12 μR/hr, then the exposure rate is 13.9 μR/hr.

The computer program provided patterns of radiation exposure rates throughout a 1-floor building and average values for unity concentrations of the terrestrial radionuclides in floor and wall material for the material and density specified in Section 3.2. Figure 2 shows the computed variation of exposure rate within structures: for the square structures considered in the calculation, the exposure rate increases near walls that contain radioactive material, but decreases if only the floor contains radionuclides. The influence of structure size on the average exposure rate within a structure is shown in Figure 3. In each case, only the U-238 (i.e., Ra-226) chain is shown in terms of the fraction of the radiation exposure rate index I, but similar curves apply to the other naturally occurring radionuclides.

Values are approximate because the U-238 and Th-232 chains were each represented by a single gamma ray of average energy and intensity. By comparison with Koblinger's more detailed gamma-ray source (Ko78), the Th-232 values were 16 percent higher at the center of the common test structure and the U-238 values were 7 percent lower, but K-40, which has only a single gamma ray, agreed within 2 percent.

The results in Figure 3, which refer only to radiation from walls and floor (not the ground outside), are comparable with the results of hand calculations given in equation (15): the exposure rates from walls and floors are 0.6 $I_{(f)}$ and 0.2 $I_{(w)}$, respectively, for a 160-m^2 structure, the one most similar in floor area to the test structure of equation (15). Comparison of Figures 2 and 3 suggests that the representative exposure rate should be measured off-center, approximately 30 percent of the distance from wall to center, as was done in the hand calculation.

In two instances, samples of concrete blocks were available at buildings with significantly elevated radiation exposure rates, and these were analyzed for radionuclide content to show that Ra-226 concentrations of 21 pCi/g were responsible (see Table 4). Where no samples could be obtained, portable Ge(Li) detectors with multichannel analyzers provided the relative amounts of the Ra-226 decay chain, Th-232 decay chain and K-40 shown in Table 13. Measurement 1, in a building where the external exposure rate was near the upper extreme of the normal range, shows approximately the same concentrations of the Ra-226 and the Th-232 chain; measurement 2, in a building with significantly elevated external radiation levels, shows approximately 10 times as much Ra-226 as Th-232. To estimate the concentration of Ra-226, the relative amounts obtained in Table 13 are substituted in equation (2) with the measured exposure rate, adjusting, however, for various other sources as in equation (15). Because the entire gamma-ray flux is viewed by the detector, the relative concentration of the elevated Ra-226 value in the main source material may be considerably higher; relatively lower concentrations in other building materials or transmitted from outdoors would tend to make the measured values more uniform.

The relative counting efficiencies obtained for the radium-226 daughter gamma rays are shown in Figure 4, together with lines drawn through these values from which relative counting efficiencies were read for the gamma rays from the Th-232 daughters and K-40. The relative counting efficiency can be

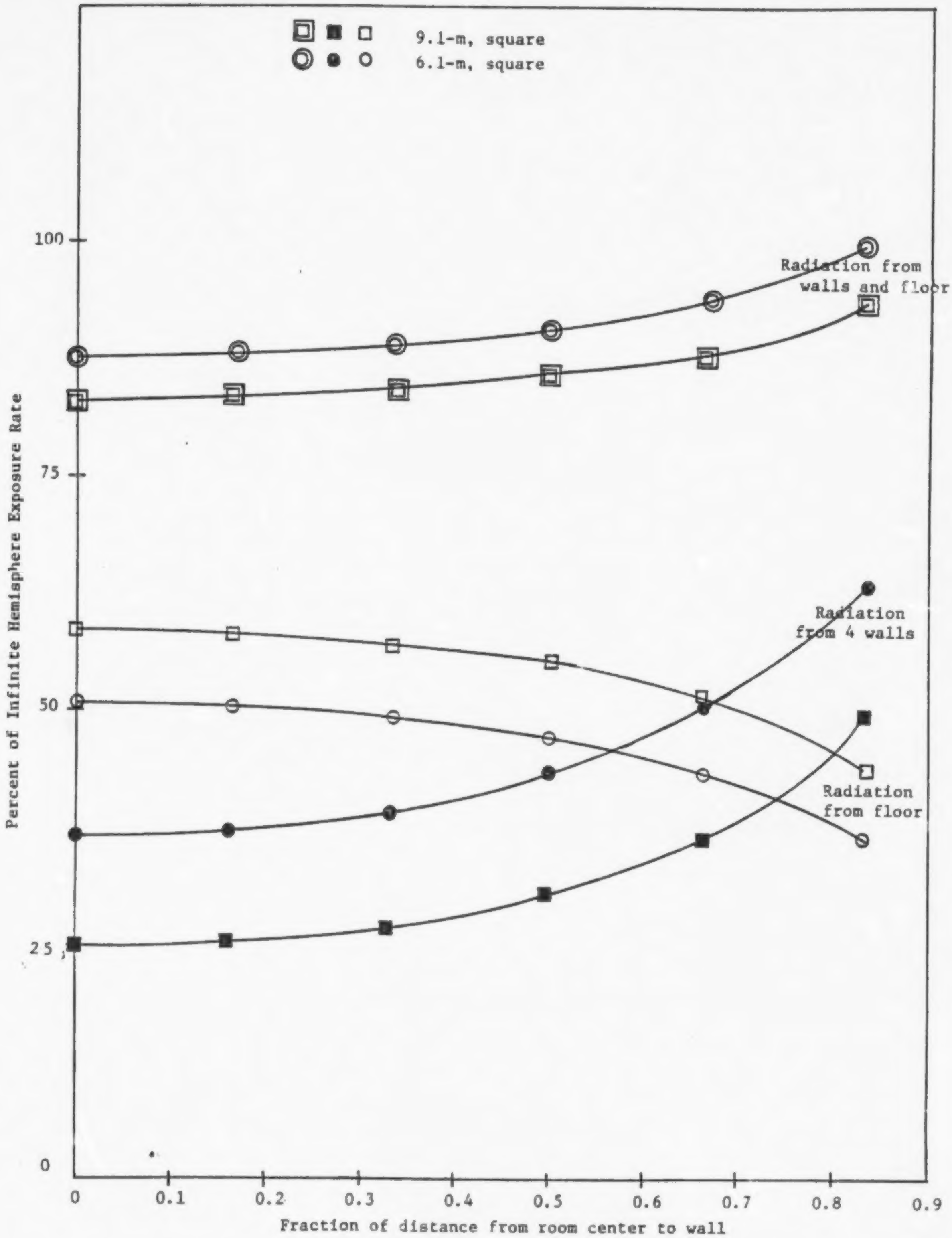


Fig. 2. Variation of Exposure Rate from U-238 Chain with Location in Structure (height above floor is 1.2m).

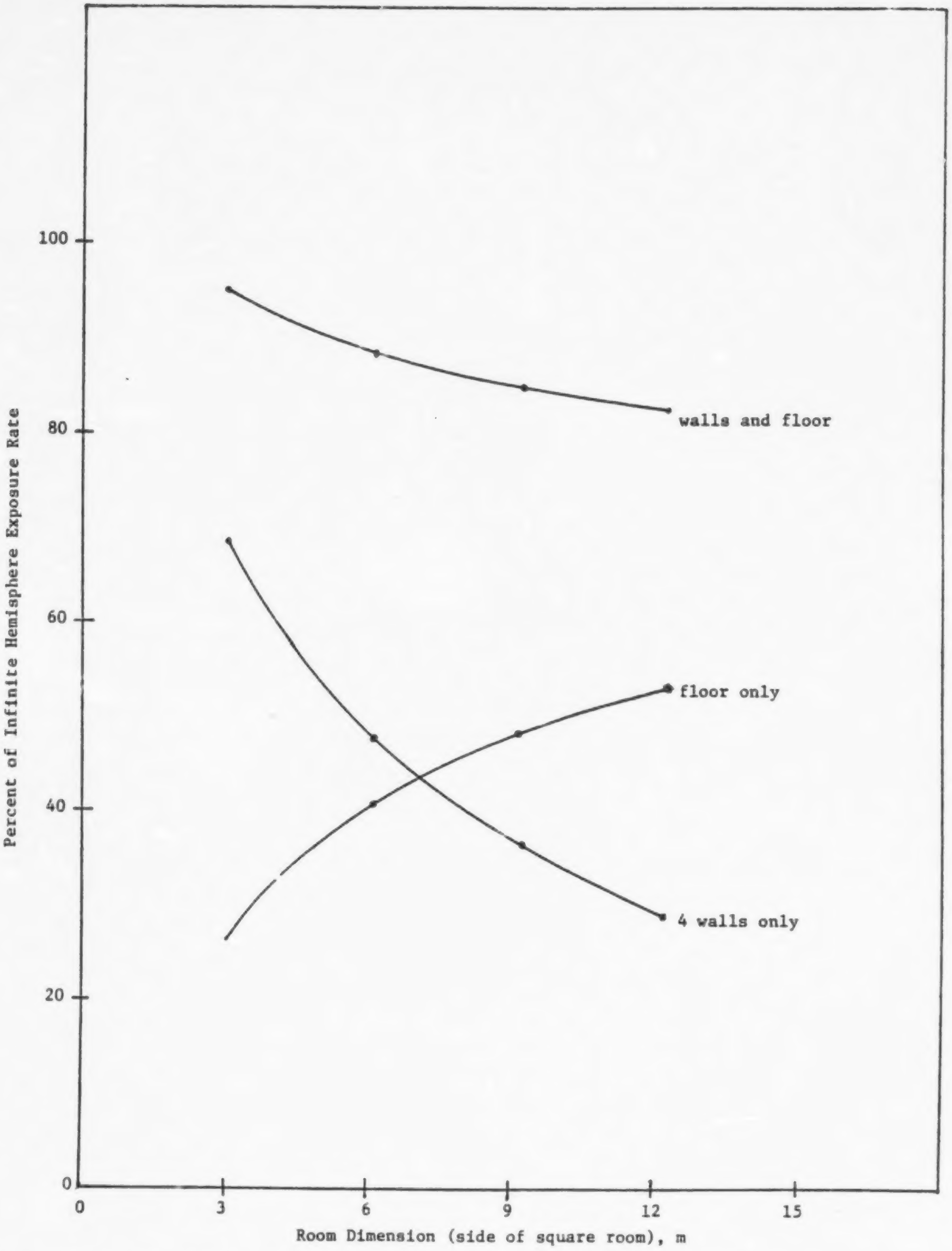


Fig. 3. Variation of Average External Exposure Rate from U-238 Chain with Size of Structure

Table 13

Use of Portable Ge(Li)-Detector Spectrometers to Distinguish Ra-226 in Buildings

			Measurement 1				Measurement 2			
Radionuclide	Energy, keV	Gamma-ray fraction	net count	relative count	rel. counting efficiency	relative activity	net count	relative count	rel. counting efficiency	relative activity
Ra-226 (Pb-214, Bi-214)	352	0.37	6,130	1.66×10^4	1.66	1.00	17,000	4.59×10^4	4.59	1.00
	609	0.46	6,680	1.45	1.45	1.00	15,200	3.30	3.30	1.00
	1,764	0.16	1,400	0.88	0.88	1.00	2,620	1.64	1.64	1.00
Th-232 (Ac-228, Tl-208)	583	0.31	4,320	1.39	1.5	0.93	1,040	0.34	3.4	0.10
	911	0.28	3,210	1.15	1.2	0.96	650	0.23	2.5	0.09
K-40	1,461	0.011	7,950	13.2	1.0	13	1,810	16.5	1.9	8.7

Notes:
1. net count has continuum subtracted from photoelectric peak
2. relative count is net count/gamma-ray fraction
3. relative counting efficiencies for Ra-226 daughters are numerically identical to the relative counts; for Th-232 daughters and K-40, they are read from Figure 2 at the appropriate energies
4. relative activities for Th-232 daughters and K-40 are relative counts/relative counting efficiencies

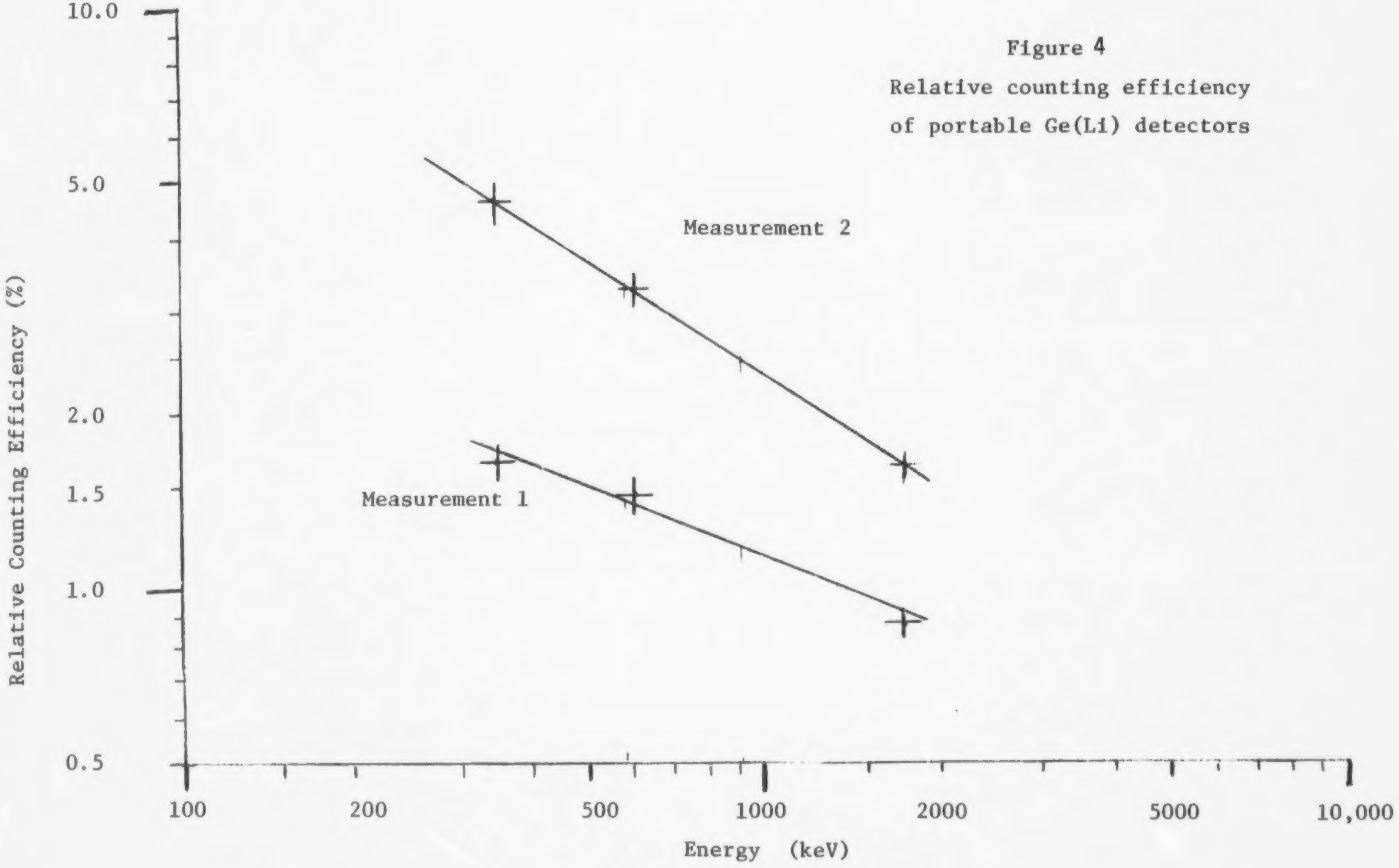


Figure 4
Relative counting efficiency
of portable Ge(Li) detectors

described approximately as a logarithmic function of energy in the range from 350 to 1,760 keV. The relation yields consistent values of relative activity for Th-232 based on either the 583- or the 911-keV gamma ray. Some deviation from linearity would be expected because of the various locations and distributions for sources of the gamma-ray flux. The two curves have different slopes because a smaller detector was used in measurement 2.

The passive radon monitors of the type shown in Figure 5, after being operated side by side to assure comparability, were exposed for 1-week periods on the second-floor in a university office-laboratory building (E), in a basement laboratory of another university office-laboratory building (O), in the unoccupied basement of a newly constructed 1-family home (S), and on the roof of the office-laboratory building E. The three structures were selected for beginning the test of the use of the monitor in a survey because of the range of expected Rn-222 concentrations. The inside walls on the second floor of building E were constructed of concrete blocks that contain elevated levels of Ra-226 (see Table 14) attributed to phosphate slag; the walls and floor of the basement room in building O are constructed with concrete blocks and poured concrete that contain Ra-226 at the upper end of the medium concentration range; and the basement room in building S has walls and floors of concrete with medium Ra-226 concentrations but, unlike the other two locations, was not well ventilated.

The results in Table 14 show relatively high Rn-222 concentrations in all three structures, as well as above-average concentrations outside. Replicate measurements, all performed within the span of 1 month, gave consistent results, as shown. The Rn-222 concentrations and WL values (if 0.4 is taken as the fraction of equilibrium of the Rn-222 daughters) attributed to sources other than outside air, are:

Structure	Rn-222, pCi/l	WL
E	2.5	0.010
O	1.2	0.005
S	2.3	0.009

The WL value in building E may actually only be one-half as large as computed because several simultaneous measurements of WL values and Rn-222 concentrations (see Section 5.2) gave an average equilibrium fraction of only 0.21. Typical values under normal ventilation rates had been calculated to be 0.003 WL in Section 2.6.

In all three cases, the computed concentrations of Rn-222 in room air from the Ra-226 in wall and floor materials were far below these values. The factors used in equation (9) and the computed Rn-222 concentrations are:

Figure 5

Passive Radon Monitor (Ge77)

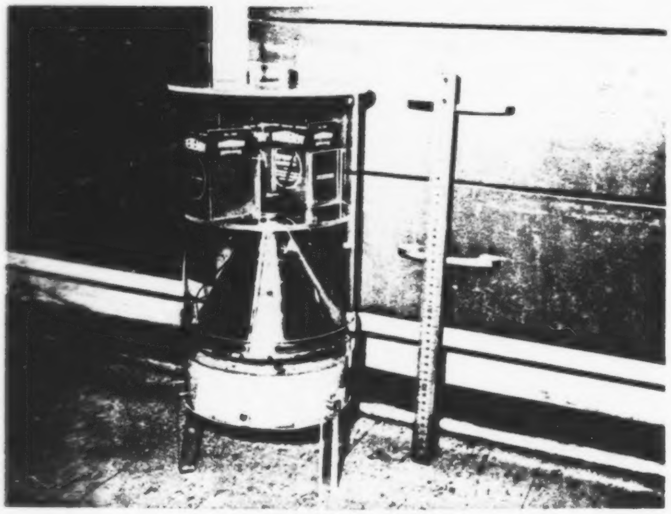


Table 14

Rn-222 Concentrations in Test Buildings

Building	Terrestrial exposure rate in building, μR/hr	Ra-226 in wall, pCi/g	Ventilation	Rn-222 concentration, pCi/l (no. of measurements)
Col. office - lab bldg., second floor (E)	28	21	air cond.	3.2 ± 0.1 (3)
Col. Office - lab bldg., basement (O)	12	2*	air cond.	1.9 (1)
Private home unoccupied, basement (S)	9.0	1.7	unventilated	3.0 ± 0.3 (2)
Outdoors	9.2	---		0.7 ± 0.2 (2)

---

* estimated from external radiation measurement and Ge(Li) spectrometry

Notes: 1. Values were measured for 1-week periods with passive collector/detector in fall, 1978

2. Exposure rates due to cosmic rays were subtracted from values measured at location of collector/detector to obtain terrestrial exposure rate

Structure	Volume, m^3	Surface area, m^2	Ventilation rate, hr^{-1}	Rn-222, pCi/l
E	4,000	2,000 (wall only)	1	0.4
O	180	100 (wall) + 30 (floor)	1	0.09
S	170	70 (wall) + 80 (floor)	0.2	0.6

The volume and surface area in building E refer to the entire second floor; the Ra-226 content of the concrete floor was not considered because it is so much lower in Ra-226 concentration. The ventilation rates are estimates only. The predicted concentrations were 1-2 pCi/l below measured values with outside Rn-222 concentrations subtracted. This large and consistent difference suggests that either the factors used to compute the Rn-222 concentrations are inappropriate or that another source of Rn-222 in building air -- for example, the ground beneath the structure -- is generally so much more important than wall and floor material that its measurement must be included in a survey of WL values in structures. In view of this observation, continuation of Rn-222 concentrations measurements in room air due to building materials appeared inappropriate until a study can be undertaken to identify and quantify the sources of such Rn-222.

3.4 Discussion

The test survey in the Atlanta metropolitan area found the pattern of gamma-ray radiation exposure rates in buildings that has previously been predicted for the U.S.: slightly lower values in wooden homes than outdoors and values equal to or slightly higher than outside within structures built with concrete block, poured concrete, brick, or stone. The typical exposure rate in wooden houses was 1 μR/hr below ambient levels, while typical elevated exposure rates in other homes were 0 to 6 μR/hr above ambient levels. The highest exposure rates in normal houses -- as much as 10 μR/hr above outside levels -- were measured at the surfaces of the radionuclide-containing materials in walls, floors, and fireplaces.

The magnitude of the incremental radiation exposure rate could be predicted by surveying building materials with a gamma-ray detector. Categories of radiation exposure potential designated broadly as very low, low, medium, high, and very high were encountered in materials. The medium category corresponds to the upper end of the range of ambient terrestrial exposure rates. The medium category was by far the most common for brick and concrete, but approximately 1 percent of these materials was in the "high" category, approximately 7 μR/hr above medium values. One of the local clays used to manufacture these building materials showed a similar elevated exposure rate potential.

In parts of two commercial buildings and three school buildings, the external exposure rate averaged 20 μR/hr above outside levels and was elevated by as much as 33 μR/hr at wall surfaces. Concrete blocks in the "very high" category were the source of this elevated radiation exposure. Two samples of these blocks contained Ra-226 at a concentration of 21 pCi/g, compared to the normal range of 1.1 to 1.6 pCi/g. These elevated levels are attributed to use of phosphate slag in manufacturing the concrete block. The slag was shipped to two Atlanta concrete producers between 1962 and 1968 from a thermal-process phosphorus production plant in northern Alabama.

The concentration of Rn-222 in one of the school buildings that was constructed partially with the concrete blocks that contain Ra-226 at a concentration of 21 pCi/g was measured on two occasions to be 2.5 pCi/l above ambient concentrations. A concentration of 0.4 pCi/l was calculated to accumulate from the concrete block according to the values in Section 2.4 The higher measured value may be due to greater exhalation rates from the material than assumed or contribution from other sources, such as the ground beneath.

The test survey showed noticeable variations in outside terrestrial radiation exposure rates. Variations of terrestrial radiation exposure rates among survey locations were as much as 8 μR/hr, and the aerial survey also observed such large changes, some of them over relatively small distances. Differences as large as 2 μR/hr in terrestrial radiation exposure rates were observed at the same location measured at intervals of several months, so that differences of this magnitude between inside and outside are uncertain. Within-home variations reached 7 μR/hr, lending importance to in-house surveys, multiple measurements, and careful consideration of occupancy in various locations if increases of this magnitude are considered significant.

Tests of the PIC and the calibrated survey meter with NaI(Tl) detector showed these instruments in combination to be rapid and reliable for measuring external radiation exposure rates in houses and categorizing construction materials according to radiation exposure potential. The PIC, which provides direct measurement of external exposure rate with only minor energy dependence between 100 and 2,500 keV, was used in selected locations inside and outside buildings to determine values in an area, and the more mobile NaI(Tl) detector was then carried about to observe variations. Such measurements require approximately 15 minutes per home; even more rapid surveys have been reported in Germany with the anthracene survey meter, where 50 surveys per day were performed (Ko78). Ra-226 can be distinguished from Th-232 and K-40 for predicting WL values with a portable Ge(Li) detector plus multichannel analyzer. Although the results are qualitative because multiple sources of gamma rays usually exist, a reasonable estimate of relative concentrations may be obtained. The passive monitor for measuring Rn-222 concentrations was convenient and sufficiently sensitive for 1-week-long measurements.

The number of structures built in the Atlanta area with concrete blocks that contain phosphate slag appears to be so large that effort needs to be devoted to finding them and assuring that dose rates do not require remedial action. Because the slag was not shipped to Atlanta after 1968 and is no longer shipped at all as of December 1978 (Ma78), no preventive action appears necessary. The following estimation of the number of structures is based on the itemized assumptions:

- 378,000 tons of slag were used for concrete blocks
- 80 percent of block by weight is slag
- typical weight of blocks used in construction is 30 tons per habitation (usually in basement) and 300 tons per non-residential structure
- one-half of residential structures constructed during this period used blocks
- 60,000 habitations were constructed during this period
- one-third of blocks used residentially contained slag

On this basis, the number of habitations constructed with slag-containing blocks is 60,000x0.5x0.33=10,000; the number of non-residential buildings is [378,000 - 10,000(0.80x30)]/(0.80x300) = 600.

The measured gamma ray exposure rates in school and commercial buildings constructed with these concrete blocks are below the level at which remedial action may be suggested according to the Surgeon General, but above the level at which use of byproduct is prohibited under the Resources Conservation and Recovery Act (see Section 2.1). Measurements averaged 20 μR/hr above ambient levels. These elevated gamma radiation exposure rates, at occupancy factors of 0.25 in schools, commercial buildings, or residential basements and a conversion factor of 0.58 rem/R would add 25 mrem/yr to the background dose of persons. For internal exposure, the calculated value of approximately 0.003 WL in indoor air is below levels that require either remedial action or prohibition of materials use. The measured Rn-222 levels on two occasions of 2.5 pCi/l above ambient air correspond to 0.01 WL above background, however, and will require further consideration and additional measurements.

4. Recommended Survey Procedure

4.1 Planning Overview

This study and the preceding work summarized in Section 2 have shown that gamma radiation exposure rates and airborne Rn-222 daughter concentrations are generally of the same magnitude within structures and outside, but that detectable differences exist in many structures and significantly elevated levels, in some. They also indicate that direct measurements on a national scale are needed to determine the effect of building materials on the population radiation dose because the present state of knowledge is insufficient to estimate incremental doses to specific population groups or to identify those at risk with any degree of reliability. Currently, only a minuscule fraction of structures in the U.S. has been surveyed for radiation exposure and Rn-222 daughter concentrations, and the radiation dose potential of building materials is known only for broad categories. The wide range of radionuclide concentrations observed in a given material and occasional discoveries of material with unexpectedly high radionuclide contents (see for example, Section 3.3) further suggest that population dose calculations not based on widespread surveys are not reliable.

Plans for a countrywide survey must consider selecting representative structures for measurement; obtaining access to these structures; measuring gamma radiation exposure rates and WL values with instruments and under conditions that yield reliable annual averages; calculating the incremental value attributable to the structure; and deriving from these incremental values the radiation dose equivalent rates to persons in the structure. To survey gamma radiation exposure rates, either one of two techniques that have been demonstrated in national surveys of West Germany (Ko78, Bu78), Sweden (Mj78), Norway (St75, St77), and Poland (Ni78), and are being tested in France (Gu78) is applicable. Gamma radiation exposure rates were determined either by brief measurement with an exposure rate meter (Ni78, Ko78, Ab78) or by long exposures of thermoluminescent dosimeters. Surveys of WL values are more difficult because incremental values within structures due to building materials at ordinary levels are usually obscured by fluctuations in the WL background. Reliable WL measurements with the commonly used Radiation Progeny Integration Sampling Unit (RPISU) are lengthy, accompanied by pump noise objectionable to many residents, and require an expensive apparatus. Hence, the proposed program determines WL increments at the present state of the art only in control structures and in buildings for which potentially high WL increments are predicted from elevated Ra-226 concentrations in building material. In all other sample structures, brief WL measurements or determinations of Rn-222 concentrations for longer periods with passive Rn-222 monitors such as the one described in Section 3.1 will assure that WL increments are below detectable levels or identify structures that have unexpectedly high WL increments for detailed monitoring.

The survey has been planned in terms of the following interrelated activities, described in detail in subsequent Sections:

1. Categorization of structures and selection of sample structures.
2. Determination of the radionuclide content of materials and the radiation background.
3. Survey of gamma radiation exposure rates in structures.
4. Survey of radon daughter working levels in structures.
5. Calculation of incremental population radiation doses and identification of populations at risk.

The second item, by establishing the range and typical values of the radiation dose potential for building materials and of the radiation background, is particularly important in guiding sample selection, finding structures with elevated exposure rates and working levels, and assuring reliability in computing incremental doses.

The survey program is recommended as a series of regional undertakings in view of the needed close cooperation with local governmental agencies to obtain access to sample structures as well as information to locate and describe the structures. Division by regions is especially appropriate because materials traditionally have been obtained locally and many structural designs have regional associations, although wider diffusion of some materials and styles is now apparent. Each regional effort must, however, be sufficiently large to justify the staff training, equipment acquisition, and data handling programs. For convenience in sample selection and data treatment, the survey areas should correspond to regions for which data bases of population size and structural types are published. These requirements will generally be met by a survey unit that is either an entire state if small or thinly populated, or a distinct physiographic area within a state, centered on a standard metropolitan statistical area (SMSA). It is estimated that under this division, the United States can be surveyed in approximately 100 regions.

The extent of the effort in the U.S. is indicated by the number of residential units given in the 1977 census for a population of 217 million persons (Bu78a):

Residence type	No of units (10^6)	No of structures* (10^6)
1-unit	53.6	53.6
2-unit	5.6	2.8
3- and 4-unit	3.9	1.1
5- to 9-unit	3.3	0.5
10-unit or more	7.6	0.2
Total	74.0	58.2

*Estimated here from number of units.

If the ratio of 0.13 non-residential parcels per residential parcel on the Fulton County Tax Digest (see Section 3.1) pertains nationally, there are also 7.6 million non-residential structures. The proposed sampling intensity is based on the West German survey (Ko78), where 30,000 dwellings were measured for a population of 63 million; proportionately applied to the U.S., this requires 103,000 dwellings and 13,000 non-residential structures, a sample of approximately 2 per 1,000 (Bu78).

The effort for a typical survey unit of 1,200 sample structures is estimated to be 9 person-years for a 3-year period. The survey is to be performed in the order given below, except that some activities will have to be repeated as new information is developed during the survey. More work will be required in surveying regions that are large in area or have numerous structures with elevated gamma-ray exposure rates or WL values.

4.2 Structure Categorization and Sample Selection

The purpose of placing structures in categories is to arrange them for sampling in readily definable sets, in each of which the gamma radiation exposure rate or WL value due to the structure falls within a narrow range. For incremental gamma radiation exposure rates, categorization must consider the concentrations of the U-238 cnain, Th-232 chain and K-40 radionuclides in the building material, the geometrical configuration of the radionuclide-bearing material, and the degree of attenuation of terrestrial radiation by the structure. The incremental WL value within structures depends on the amount of Ra-226 in the structure, its geometrical configuration, the fractional exhalation of Rn-222 from the material, and the residence time of Rn-222 daughters in room air.

In the cited national exposure rate surveys (see Table 1), structures have generally been grouped by materials of construction for exterior walls -- a readily recognizable category that distinguishes the higher exposure rates from stone, poured concrete, concrete blocks, and bricks compared with timber and various prefabricated composition materials. In some instances, specific man-made and natural materials have been identified as responsible for elevated radiation levels in brick or concrete. One influence of geometrical configuration is the generally higher exposure rate and WL value in basements than on the ground floor, and a further decrease of the exposure rate above the ground floor (Mo76). Similar categories applied to WL values do not always result in the same distinct groupings (see Table 2), probably because small incremental values are not as readily observable and the other factors cited above play such important roles.

For this survey, an initial categorization by exterior material is recommended according to the system used by HUD-FHA (FH78):

Frame	Masonry	Combination
wood shingle	brick or stone	
asbestos shingle	stucco or concrete	
fiber board	aluminum	
brick or stone	other	
aluminum		
other		

Because statistics on the fraction of FHA-mortgaged 1-family homes constructed with these materials are published at frequent intervals, the dose increments determined for these categories can be calculated for distinct regions or for the U.S. as a whole. Information concerning structural types, age, and cost is also available from this source. Caution must be exercised in applying these statistics because they are based on only 0.2 million homes that may not be typical with regard to price and location.

Based on the information in Section 2, it appears useful to separate brick and stone, concrete and stucco, and poured concrete and concrete blocks in the above categories and to include material for floors, such as poured concrete and wood, among wall categories. Materials used in the interior of structures that may also contribute to the radiation dose such as phosphogypsum and ceramic tiles, stone and brick in fireplaces, concrete block walls and concrete pillars, must also be enumerated. Within each category, representation must be given to structural types such as 1-family homes with basements, on slabs, or with crawl spaces, and constructed on one or multiple floors. Subcategories are needed for materials that contain constituents unusually high or low in radionuclide content, as discussed in the following Section. Differences in gamma-ray exposure rates were observed between old and recent masonry homes (Ko78), but these may be resolvable on the basis of the constituent subcategories. If the wood and prefabricated wall categories consistently show similar low exposure rates and WL values, they may be combined in order to focus more effort on categories with elevated levels. For WL values, structures must also be categorized by ventilation rates and the ratio of the surface of radium-bearing materials to room volume. It is anticipated that approximately 50 categories and subcategories will be utilized per region. Because published national statistics are not sufficiently detailed for some of these categories and unavailable for others, much of this information must be determined locally.

The necessary statistics for categorizing and enumerating structures and then locating samples are usually difficult to compile; obtaining them requires combining examination of public documents, inquiries of specialists, and a visual survey of structures. Documentation is available where building permits are needed, which currently pertains to more than 85 percent of new construction. Real estate tax duplicates and private organizations (e.g., the Sanborn Map Company) that compile data for land use planning and setting casualty and insurance rates also are sources of tabulated information. Among specialists' groups are boards of realtors, builders' associations, and associations of construction material suppliers within the survey area. These can provide building statistics, describe the types of structures and materials in various areas, and refer inquiries to persons who specialize in areas, periods of construction, sources of materials, and construction practices. Once the survey team has become familiar with such practices in the survey area, use of detailed maps and visual surveys by automobile or helicopter can confirm exterior classifications and enumerations, and select sample structures for measurement.

Gaining access to the selected sample structures is a skill that must be developed by each survey team. In the present study (see Section 3), new residences under construction in several subdivisions could be surveyed after describing the study to the builders, permission for measurements was obtained from persons responsible for government, industrial, and educational buildings, and participants in the study measured structures in which acquaintances lived. Access to occupied residences and commercial facilities may be attained through survey descriptions and appeals for participation in news media and to specific groups such as staffs of government agencies, college faculties and students, civic clubs, church organizations, industries, and labor unions.

The statistical information and ancillary observations must be collected and stored in consistent form in all survey regions. Sufficient sample structures are selected in each category and subcategory to obtain statistically reliable radiation data for the type of structure, material, and other factors known to influence the radiation dose. This requirement should be readily attainable with an average 1,200 sample structures per regional survey (see Section 4.1) and approximately 50 categories and subcategories further divided by structural type. A balance in sample selection is required between achieving geographical coverage and using time most effectively in surveying.

4.3 Determination of the Radionuclide Content of Materials and the Radiation Background

The foundations for the survey of gamma radiation exposure rates and WL values in structures are established by determining the radiation dose potential of building materials and mapping the natural radiation background in the region. Determination of the dose potential for materials in the region prior to the building survey establishes typical levels and identifies materials within a category that should be considered separately because they are unusually high or low in radionuclide content. Most importantly, it is a systematic approach for finding structures that result in elevated radiation doses. Background mapping locates suitably representative sites for measuring ambient WL levels, defines the magnitude of the terrestrial gamma radiation and Rn-222 daughter backgrounds throughout the region that must be subtracted from indoor measurements, and indicates areas where extreme external radiation levels or sudden changes in levels require careful analysis of data obtained within structures.

The study described in Section 3 demonstrated a simple procedure for determining the radiation exposure potential of materials by placing a sensitive gamma-ray survey meter against a sufficiently large amount of the material at a supply yard, construction site, or in an existing structure. Even a survey meter not calibrated in μR/hr can group building materials as very low, low, medium, high, and very high -- the categories used in Tables 4, 6 and 7 -- if it is sufficiently sensitive. By calibrating the detector, considering the background value, and using the calculations appropriate to the structure under consideration as shown in Section 3, the inside gamma radiation exposure rate can be estimated. Special attention is then given to determine the causes of either very high or low radiation levels from materials and to formulate corresponding material subcategories for selecting sample structures and computing population doses.

If the radiation exposure potential of a material is found to be elevated, it is important to determine whether the radiation is from Ra-226, the source of Rn-222 and its daughters. The material can be analyzed for Ra-226 as described in Sections 3.2 and 3.3 by taking samples to the laboratory for gamma-ray spectral analysis or, if no samples are available, obtaining a gamma-ray spectrum in situ with a portable detector and spectrometer.

If a material shows significantly elevated radiation exposure potential, it is particularly important to determine the extent to which it is used and identify all places of use. In the study described in Section 3, this was done by analyzing the radionuclide content of the material, identifying its constituents through inquiries with suppliers of the material, confirming the elevated radionuclide content of the constituents by analysis, and tracing the radioactive constituent to its source. The various uses of this constituent are then delineated by further inquiries with suppliers and additional measurements.

Mapping the terrestrial gamma radiation levels of a region is conveniently performed by aerial overflights; the resulting maps are available for numerous areas in the United States examined for uranium prospecting or for radiation protection at nuclear facilities (Bu72). Earlier maps, such as the one in Figure 1, have isopleths in terms of count rates that must be compared to ground truth for determining exposure rates. More recent maps have isopleths of exposure rates 1 meter above ground. Precision and sensitivity depend on the height and intervals of the overflight (Bu72). Typically, an overflight at 200 m height and 300 m intervals can locate isopleths at a 2 μR/hr intervals within approximately 100 m and detect point sources equivalent to 15 mCi Ra-226. Such overflights will not detect individual residences constructed with materials of somewhat elevated radioactivity content -- 30 tons of poured concrete and 30 tons of concrete blocks each with a Ra-226 content of 10 pCi/g would only constitute a 0.6-mCi source -- but will identify extensive use of radioactive material. The mapped levels are especially useful for correcting elevated or lowered values caused by nearby structures, pavement, or other artifacts that were measured outside sample structures.

Ground-based radiation exposure surveys with large NaI(Tl) detectors in vans (Ha78) take much more time but through proximity are more responsive to small variations and more sensitive to radiation from structural materials. Reported calibration data (Ha78) suggest that Ra-226 concentrations as low as 25 pCi/g will show detectable elevations in meter readings at a distance of 8 m if the background radiation is reasonably uniform.

Because area surveys of the ambient gamma radiation exposure rate are usually obtained only once, a complementary program of background gamma radiation measurements throughout the year is needed to obtain annual exposure values. Readily observable fluctuations in the terrestrial radiation exposure rate are caused by variations in radon emanation from the ground and in the attenuation of gamma rays from the ground by water and snow (see Section 2.1). In contrast to radiation mapping, which should be performed prior to the radiation exposure survey of structures, these measurements are performed most efficiently during the survey, at locations that provide background information for survey structures and will examine the entire range of factors cited above. The measurements can be performed either by exposing TLD's for successive periods of one to three months for the entire year, or by briefly reading a survey meter on frequent -- for example, weekly -- occasions throughout the year.

Determining the pattern of WL values throughout the survey area and its variation with time is even more necessary than mapping the gamma radiation background because WL values are usually more variable. The fluctuations are also less predictable at the present state of knowledge. Primarily, regions of similar ambient WL values must be defined to locate representative sites for ambient WL monitoring. Such regions can be identified by physiographic patterns, making distinctions among areas next to large bodies of water, ground that has significantly higher or lower Ra-226 concentrations, and land separated by obstacles such as mountain ranges that interfere with the free flow of air. Comparison of WL monitors operated for weekly to monthly periods throughout the region for a year will define more precisely each area of uniform WL value within which a reduced number of monitors can provide outside WL data for subtraction from indoor values. These multiple measurements can also be used to determine measurement uncertainty and to relate ambient WL values to factors such as local emanation rates from the ground, atmospheric stability, precipitation, wind direction, and snow cover that affect radon levels in ground-level air.

Control measurements should be performed in structures that contain so little Ra-226 that their building materials do not contribute significantly to WL values in room air, to assure that measurements of WL values outside can predict background levels inside. These measurements are performed in structures that represent each of the material categories and the structural types identified in Section 4.2, and should include the entire range of ventilation rates and radon exhalation rates from the ground. If a number of preliminary measurements confirm the applicability of data from outside WL monitors to room air, this effort can be discontinued; if other significant sources or pathways of Rn-222 are identified -- for example, radon diffusing from the ground through basement walls and floors, measurements to delineate these sources will be required.

4.4 Survey of Gamma Radiation Exposure in Structures

Two methods that can both be recommended have been demonstrated on national scales for surveying gamma radiation exposures in structures. Brief measurements with a portable plastic scintillation detector were used in West Germany (Ko78). A similar procedure demonstrated in Section 3 of this study utilized a PIC as a portable but heavy direct-reading dosimeter and a NaI(Tl) detector as a more convenient survey meter that was calibrated relative to the PIC. In Sweden (Mj78) and France (Gu78), TLD's were exposed for extended periods in structures. The two methods were found to be comparable in Poland, where they were applied side by side (Ni78). The survey meter in the Polish survey was a pressurized ionization chamber of somewhat different design than the one used here, and the TLD's were LiF chips.

The general approach recommended for either technique is to obtain measurements within the selected sample structure at a limited number of locations -- some that represent exposures to humans and others that indicate maximum exposures -- and in the environment to determine the background exposure levels. The survey locations must be comparable in all similar structures to permit data compilation, and in sufficient number to provide reliable statistics within the constraints of available personnel and instruments. Thus, initial representative measurements of human exposure can be one or two per floor, at least 1 meter distant from the wall, and preferrably approximately one-third of the distance between wall and room center and 1 meter above the floor. One measurement of maximum exposure can be performed against each surface of material expected to be elevated in radionuclide content. In structures covering large areas, some additional measurements per story are desirable, while in tall structures not every story need be measured. Complex structures with various wall and floor materials, including inside walls with possible elevated radionuclide content, will require additional measurements. The outside background is measured at one or two locations near the structure, but sufficiently distant to avoid radiation from walls and floors.

A survey conducted by brief measurements with survey meter can be highly responsive to complex exposure-rate patterns because even a rapid survey within the structure will indicate typical levels, sources of elevated exposures, and problems such as distinctly different exposure rates in various rooms. The study in Section 3 has shown that systematic measurements are best obtained by carrying the survey instruments around each room available for inspection and stopping briefly at predetermined comparison locations, off-center, to record an exposure rate value. In many instances, the exposure rates are similar throughout one floor, so that a single value is representative. Materials that cause elevated radiation exposure rates are indicated by changes in meter readings while structures are being surveyed, and can be characterized by a meter reading taken at the surface of the material. External background exposure rates are measured by carrying the survey meter around the house at a distance of approximately 4 m to determine whether a uniform background can be recorded or the background differs at several locations. Significant variations in background values outside the structure suggest caution in attributing exposure rates in the basement or ground floor of the structure to building materials and the need for a more detailed survey inside. If the outside walls or floor of the structure are sources of elevated radiation exposure rates, background measurements must be performed at a greater distance, selected by observing the reduction in meter reading with increased distance. If appropriate background measurements can not be performed because the ground is paved or other structures interfere, an estimate must be based on the measurement plus a correction factor or on values from the nearest available background sites, although the estimate becomes more uncertain with increasing correction factor or distance from the structure.

Advanced planning can make a survey by brief measurements most effective by selecting nearby structures where possible, mapping routes for minimum travel time, and arranging access with minimal delay. Because attaining access is crucial, considerable planning effort needs to be devoted to developing cooperation by the surveyed population and scheduling the survey appropriately. The major disadvantages of brief measurements are intensive use of personnel and inability to determine the average exposure rate for the year. To compensate, sufficient year-long measurements must be obtained at background locations and control structures, as indicated in Section 4.3. The instantaneously measured value is compared to the curve of exposure rate vs. time of year and adjusted to correspond to the annual average exposure rate.

The drawbacks of brief measurements are avoided by exposing TLD's for a year, for example in four successive three-month periods. In the Norwegian survey, the TLD's were mailed out and returned by mail, which minimized personnel effort. Instructions are given to place the TLD's at the locations indicated above. In dwellings, for example, representative locations are one or two per floor, but not directly on walls or floor, possibly taped to the bottom of a table-top (Ni78). Additional TLD's are affixed to materials that may be sources of elevated radiation exposures within structures, and two TLD's are attached to trees or fences at separate locations outside the structure. The mailing must include detailed instructions and forms to be filled out by the resident, owner, or caretaker, that describe the structure and give the location of the TLD's, the period of exposure, and any information that may have a bearing on the TLD exposure. Approximately twice the number of structures required for the survey should be included initially to allow for lack of cooperation, discontinuation, dosimeter mishandling, and errors. Special consideration needs to be given to assuring minimum and defined background radiation exposure of the TLD's during transit in the mail by mailing control TLD's, prompt handling, and avoidance of exposure to radioactive material shipments.

Some contact with the cooperating persons and observations of the sample structures by the survey team are desirable to assure that the buildings are in the appropriate category, the TLD's are exposed as reported, and the participants are reliable. It is anticipated that each sample structure will be observed at least from the outside while being selected (see Section 4.3), and that the structure will be entered and the survey discussed with the participant during the brief WL survey (see Section 4.5). If the latter is performed soon after reading the first-quarter TLD's, any unusual exposure-rate readings can be discussed with participants and checked by brief surveys with exposure-rate meters.

If sufficient survey personnel are available to distribute and collect the TLD's, most of the potential problems with misunderstanding or misinformation associated with mailed instructions and responses can be avoided and the background received by the TLD's in transit is more controllable. The TLD's can often be placed more effectively by the survey team, situations that require special TLD placement can be dealt with immediately, and the causes for unusual or puzzling exposure-rate readings can be explored by visual and radiation-meter survey.

In summary, surveys using either the brief measurement with survey instrument or year-long exposures of dosimeters are considered suitable, and varied approaches in different regions may even be desirable, depending on staff capabilities and exposure-rate conditions in these regions. It is important that the measurement locations within the sample structures be comparable and that survey instruments and dosimeters be intercalibrated to yield identical readings. Furthermore, survey regions that use TLD's will find some application for survey meters in exploring exposure-rate anomalies, and regions that use survey meters primarily may wish to determine annual exposure rates at control locations with TLD's.

4.5 Survey of Rn-222 Daughter Working Levels in Structures

All sample structures will be examined for radon-daughter levels, but detailed measurements of WL values will be restricted to selected groups. The calculations performed in Section 2.4 are supported by observations that suggest that Rn-222 daughters due to building materials that contain the usual concentrations of Ra-226 are not readily detectable at normal ambient WL values and ventilation rates. The measurements for at least 100 hours on four occasions to obtain reliable WL data also require numerous samplers per survey, and the operation of the usual air pumps for long periods at locations of common occupancy can be objectionable. Hence, these measurements will be performed mainly in structures built with materials that contain Ra-226 levels so elevated that the resulting WL values are expected to contribute noticeably to the total WL value in room air. Such structures will be selected for measurement on the basis of the Ra-226 concentrations in building materials found in the materials survey by analysis of samples or by in-situ gamma-ray spectroscopy discussed in Section 4.3. Detailed WL measurements will also be performed in selected control structures and at outside background locations (see Section 4.3). The remaining sample structures will be surveyed briefly to assure that Rn-222 concentrations are not elevated due to building materials, and to recommend increased ventilation rates or plan inclusion in the WL survey for any that have elevated levels.

The selection criterion for structures with elevated Ra-226 content is at present uncertain because of the questions concerning the sources of Rn-222 in building air indicated in Section 3.3, and will depend on the initial observations in these surveys, unless current surveys and studies in the meanwhile provide this information. Moreover, the extent of detectability depends on ambient WL values and their fluctuations. If the estimates in Section 2.7 are applicable, Ra-226 concentrations of approximately 12 pCi/g in walls and floor would result in detectably elevated WL values. Similar values would also result from lower Ra-226 concentrations at proportionately lower ventilation rate or higher wall surface/room volume ratio, or if the Rn-222 exhalation fraction or Rn-222 daughter-to-parent fraction were larger values than estimated in Section 2.4. The gamma-ray exposure rate that would correspond to this Ra-226 content would be readily detectable.

In structures found to have elevated gamma radiation exposure rates corresponding to this Ra-226 concentration, a sample of building material will be analyzed to determine whether the elevated gamma-ray exposure rate is mainly from Ra-226 or from radionuclides that would not result in high Rn-222 exhalation. If no material is available for analysis, the wall or floor that is the source of the high exposure rate can be analyzed *in situ* with a Ge(Li) detector as shown in Section 3.3 to determine qualitatively the contributors to the gamma-ray spectrum. If Ra-226 is found to be the major constituent, the structure will be included in the WL survey.

Structures with high Ra-226 content in building materials and the control structures will be monitored for 1-week periods during each of the four seasons with RPISU or equivalent instruments in locations that are predicted to be the major sources of doses to occupants, taking into consideration the occupancy factor. In many cases, this location is expected to be the basement. All locations believed to be significant sources will be monitored. As an initial estimate, these structures with elevated Ra-226 content will comprise approximately 5 percent of the sample structures, and replicate control measurements for each structural category will add an additional 10 percent. In addition, sufficient outside WL monitors must be operated continuously during the whole WL survey, as discussed in Section 4.3, to determine ambient WL values throughout the region of the structure survey. At least one control structure should be monitored for inside WL value to parallel each outside monitor. The ventilation rate must be determined for each WL value within a structure. Measured values will be compared with values calculated from ambient values, the estimated Rn-222 exhalation rate from building materials and the ventilation rate, and any cases of discrepancy will be examined to determine the causes.

All other sample structures will be measured either briefly for WL values or for longer periods for Rn-222 levels, utilizing an instrument such as the RPISU or an air filter with spectral analysis or multiple measurements for the former and a passive Rn-222 detector for the latter (see Sections 3.2 and 3.3). The ventilation rate will be estimated to compare predicted with measured WL values or Rn-222 concentration. Brief monitoring will also be performed at secondary locations in structures with high Ra-226 contents to estimate the distribution of Rn-222 daughters in building air.

Additional measurements will be performed in structures that show distinctly elevated WL values where gamma radiation exposure levels have not been proportionately high, or that show occasional elevated values not consistent with calculations. A search will be undertaken for sources of Rn-222 that could account for elevated WL values in room air. Potential sources are the ground beneath the structure, gas or water used in the structure, and radium-containing products.

4.6 Calculation of Incremental Doses and Identification of Population at Risk

Gamma radiation exposure rates and WL values will be recorded for the measurement locations and for any other occupied locations in the structure where brief measurements may have suggested their contribution to the doses of occupants, together with the outside background values for that structure that have been measured or inferred. Multiple measurements within the structure will be averaged if appropriate, as will background values. Distinctly different values will be treated separately to compute doses on the basis of occupancy. Adjustments will be made for variations in these values throughout the year where brief measurements were performed, relating them to control measurements performed during the entire year. These total and background values will be compiled in material categories, with representation for structural types and subcategories for levels of radionuclide concentrations in materials, ventilation rates and building volumes per emanating surface areas, as these factors affect either gamma radiation exposure rates or WL values.

Because the gamma radiation exposure rate inside a structure is not a simple sum of the outside exposure rate and the contribution from building materials, subtraction of outside from inside measurements may not yield comparable data for different structural categories. This holds true also for WL values in room air that depend on the multiple factors cited in Section 4.5. In structures that contain little or no radioactivity in their materials, the gamma radiation exposure rate inside appears to be a fraction of the outside value, as indicated in earlier reviews (Mo76) and shown in Section 2.3, and thus may be best reported as the fraction of outside gamma radiation exposure rate. Relating inside to outside exposure rates by ratio also appears to be appropriate if indigenous materials are used, i.e., the radionuclide concentration in the material is similar to the ground. For structures with walls that contribute most of the inside gamma radiation exposure rate within and contain higher radionuclide concentrations than the ground, however, equation (15) suggests that the difference between inside and outside values gives the more appropriate increment. For a systematic approach, it is suggested, therefore, that where gamma radiation exposure rates within the structure are similar to or less than outside, the increment be calculated as a fraction of the outside value, while for higher values inside, the increment be calculated as the difference. Insight into the relation between the source of radiation and the exposure rate is obtained most effectively by considering a model such as the one in Sections 3.2 and 3.3, but a more elaborate calculational program is needed for more accurate predictions, and further studies will be required to confirm the model. Moreover, utilization of the model requires considerable ancillary information to describe the geometrical configuration of sources and detector.

For WL values, the difference between inside and outside measurements represents the value due to building materials only in the absence of other sources. Thus, elevated WL values will also have to be considered in terms of a calculational model before they can be attributed to Ra-226 in building materials. If other sources have been eliminated, then the effects of ventilation rates, exhalation fractions, and room volumes relative to exhalation surfaces can be recognized by creating appropriate subcategories for compilation.

For each category and subcategory, the averages, standard deviations, and ranges need to be calculated to describe relative radiation dose impacts and to identify materials, structures, and behavior of occupants that lead to significantly elevated doses. These values are then combined with the number of occupants, the occupancy factors, and conversion factors to dose equivalents to compute both population dose equivalents and dose equivalents to the most exposed persons. All categories and subcategories that have significantly elevated doses will be considered in detail to search for other structures where persons may be exposed to such doses.

To maintain comparability of results among the numerous survey regions, one or more centralized groups must provide calibration services for instruments, quality assurance programs for the measurements, and data compilation facilities. Prompt dissemination of observations is desirable to alert other survey teams to findings of elevated gamma-ray exposure rates or WL values in certain structures or of elevated radiation dose potentials in materials. Initiation of a few pilot surveys before the rest will permit development of detailed protocols and perfection of techniques for selecting and surveying sample structures.

5. Methodology for Cost-Effectiveness Determination of Sealant Processes for Radon Containment in Building Materials

5.1 Introduction

Culot and Schiager (Cu76), and Auxier et al. (Au74) have proposed that the exposure to radon daughter inhalation in buildings can be reduced by coating floors and walls with appropriate materials. The principal evaluations of such coatings are by Franklin et al. (Fr75) and Hammon et al. (Ha75); effectiveness of a coating was demonstrated in recent tests by Culot et al. (Cu78).

For the purpose of cost-effectiveness estimates the following information must be established:

A. Dose reduction

Radiation exposure in buildings is made up of three components:

1. Natural background from cosmic rays and terrestrial radioactivity. This is reduced to a small extent by the structural features of the building itself.
2. Gamma radiation exposure due to potassium-40 and uranium and thorium daughters in the building materials. This decreases with the distance from surfaces containing these radionuclides. Average exposure levels have been computed (see Section 3.3); the resulting exposure rates depend on room dimensions, while population dose equivalents depend on the extent of occupancy.
3. Radon daughter inhalation. This depends mostly on radium-226, and to a lesser extent thorium, concentrations in the building materials, the permeability of the material to radon exhalation, and its effective surface area. Radon daughter concentrations in room air depend on room size and ventilation (see Section 2.4). The extent of the internal radiation population dose depends on the occupancy factor by persons.

B. Exposed population

Since both gamma-ray and radon daughter dose levels in buildings due to construction materials appear to be low in most instances, reduction measures should first attack situations where the population dose is highest, to be reasonably cost-effective. This would apply for the following cases:

1. Materials that have a high total uranium and thorium content because of geographical and geological preponderance of such materials in concrete or brick.
2. High-Ra-226 materials in buildings with relatively high population use, either in major metropolitan centers or in public buildings such as schools, hospitals, and auditoriums.

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This requires identification of major sources of materials with high Ra-226 content to control their supply, and of population centers where their use in construction is prevalent.

C. Choice of coating materials

To control radon emanation from concrete blocks and floor surfaces, certain paints, varnishes, coatings and primers may be employed. These must be classified according to their permeability, adherence to the substrate, continuity of surface film over long time periods, resistance to wear, flaking and cracking, ease of consistent application, cost and availability.

Comparative tests of coatings have demonstrated the effectiveness of a multilayered seamless epoxy coating applied in 4 days to a thickness of 4.1 mm (Cu78). Tests are also being performed here on a coarse concrete block wall (see Section 5.2), in which the sealant is applied by painters to ensure typical professional work. A number of materials, such as epoxy paints, "water proofing compounds", latex paints, and oil-based paints may be effective, although differing in the degree of surface priming required and their sensitivity to concrete moisture content.

D. Effect of ventilation

Work at Grand Junction and in uranium mines has illustrated how radon daughter concentrations can be reduced appreciably by high rates of ventilation. This implies both dilution and introduction of filtered air rather than just circulation of cooled and dried or humidified air. In homes and public buildings this approach is difficult to quantify because high ventilation rates prevent attainment of equilibrium among radon daughters and also may promote higher rates of radon exhalation from wall materials. Since air circulation in homes and public buildings, if used for radon daughter control, would have to operate continually regardless of weather conditions or power usage, it should be regarded as undesirable as a preventive measure, although attractive as a means of additional, optional dose reduction.

5.2 Measurement of Sealant Effectiveness

One of the major potentials for remedial action depends on evaluation of various paints and sealants for their effectiveness in controlling the emanation of radon from the surface of walls and floors. Previous measurements reported in the literature (Au74, Cu76, Cu78, Fi76, Fr75 and Ha75) had been concerned primarily with mine surfaces and the control of radon daughters from mill tailings; the surfaces examined and the methods of measurement were rarely applicable to ordinary structures. The present work indicates that concrete blocks containing radium-bearing aggregate are an important building material to consider, hence the measurements were confined to a study of such blocks as used in actual wall construction. Purely fortuitously, a building on the Georgia Institute of Technology campus was found to be constructed of such blocks with a relatively high level of Ra-226 content.

To evaluate the sealant effectiveness of various coatings, one must consider the different effective surface areas and porosities of concrete blocks. Surprisingly, no industrial standard or uniform description appears to be available for surface area, roughness or porosity for concrete blocks. Consequently, any measurement on coatings may relate only to the particular structural block which, however, can be described as typical of the producer of high-radium blocks in Atlanta.

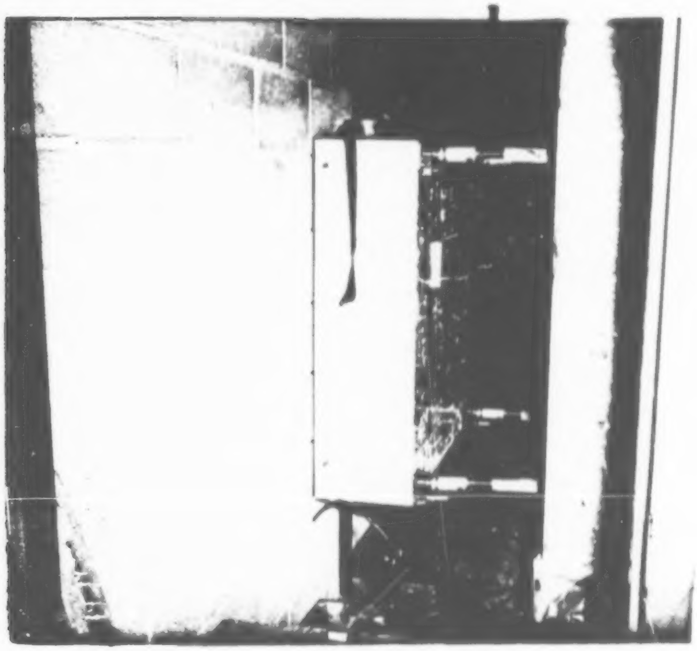
Similar considerations apply to the mode of application of coatings. There is no standard method of applying paint to rough walls and even applying a specified number of coats is no guarantee of reproducible coat thickness or absence of pinholes or other irregularities. To achieve a "typical" condition, coatings were applied by professional painters working under normal conditions.

Sealant effectiveness was determined in a moderately ventilated service chase with bare exposed concrete block walls, approximately 3.6m x 25m per wall, with 1.3m distance between walls. Measurements were obtained by two methods:
a. Radon daughters were measured by collecting particulates under conditions of long-term air circulation. The air sampling and radon-daughter collection system was a Radon Progeny Integrating Sampling Unit developed at Colorado State University. These units were constructed on the pattern of a RPISU lent by the EPA Montgomery Laboratory. Airborne particles, including Rn-222 daughters, are collected on a 1.3-cm-dia. membrane filter. An annular CaF:Dy thermoluminescent dosimeter faces the filter to record the alpha-particle decay energy of the radionuclides on the filter. A second TLD, identical in form but separated from the first by a stainless steel washer, records the gamma-ray background dose for subtraction from the total dose on the first TLD. Both are measured with a TLD reader (OR75). Two of the annular TLD's exposed to known Rn-222 daughter concentrations in air by staff of the DOE Environmental Measurements Laboratory showed factors of 71 and 61 μWL per exposure unit reading.
b. Radon-222 was measured by adsorbing the gas on activated charcoal from circulated air in a similar closed system. Two successive 4.6-cm-dia. columns of 6-14 mesh activated coconut charcoal, each containing 480 cc, collected Rn-222 from air. The charcoal was transferred to a container calibrated for gamma-ray detection efficiency, held for 3 hours to assure equilibrium concentrations of Rn-222 daughters, and analyzed with a Ge(Li) detector and multichannel analyzer. Comparison of the amounts of Rn-222 on the first and second column indicated that 90-95 percent was retained per column at ambient temperatures (20-25°C).

In both cases, a large 250-liter plywood box was pressed against the wall by means of a set of jacks. An airtight seal was obtained around the edges of the box by means of a foam-rubber strip material. In this way, an area of the order of one square meter was sampled in a consistent fashion in a closed system. After attaching the box, a period of two hours was allowed to permit decay of existing radon daughters. Air was then circulated, by means of a pump, from the box through a filter assembly and a charcoal bed. Figure 6 shows a photograph of the system in position. Air flow was maintained at approximately 0.5 liter/min for 5 to 30 hours in various tests. At the beginning of each run, air was drawn into the box from the outside to maintain consistent airborne particulate concentrations.

Figure 6

Test of Sealant Efficacy
to Reduce Radon Exhalation



The materials, tested by preparing 1.5-m square surface areas, were: 1. block filler, a thin plaster compound; 2. CAMCO water-soluble masonry paint, single coat; 3. CAMCO semigloss latex enamel paint, water soluble; 4. Pittsburgh "Aquapon" polyamide epoxy paint, and 5. Bonsal "Surewall" surface bonding cement, a waterproofing compound. Before applying these materials, the bare surface areas were tested to assure that they were similar in radon emanation to the rest of the area.

Preliminary runs with the TLD system obtained information on optimum decay periods and recycle conditions. Table 15 summarizes the results of subsequent runs both for TLD (radon daughter) readings and the Rn-222 determinations on charcoal. There was considerable scatter in the results and the averages should be considered to be indicative only. The two sets of measurements for the bare wall show an equilibrium fraction of 0.21 for Rn-222 daughters. It is evident from these and other, less well correlated, determinations of sealant effectiveness that only the plastic sheet sufficiently reduced radon exhalation. None of the sealant materials did so, although substantial diminution was obtained with a single coat of epoxy paint, both with and without the block filler. In practical cases, the effectiveness of this coating can presumably be increased by extra coats; however, it also will vary with the smoothness and porosity of the material.

Although the WL measurements provide needed quantitative data on surface sealants, one may raise some questions regarding their significance. The TLD measurement depends on the availability of particles to serve as attachment nuclei. Early measurements showed a significant depletion with time which affected longer runs and for this reason the present procedure was adopted to replenish particulate levels. However, no assurance could be obtained that these levels remained constant over a period of many weeks. The Rn-222 concentrations obtained by collecting radon on charcoal reflect both emanated Rn-222 and residual background radon concentrations initially in the collector; under the conditions of the experiment, mostly the latter was measured. To determine the fraction of radon passing through the sealant, either numerous box volumes of air must be circulated through the charcoal collector to minimize the contribution by the Rn-222 initially in the box, or the initial Rn-222 content of the box must be permitted to decay.

In practice, the nature of the surface is an important factor in controlling radon exhalation. There appears to be no industry standards governing roughness or porosity of concrete products. Epoxy coatings can be applied, but care must be taken to fill in pores and cracks and to minimize surface wear with time. Plastic sheets or, perhaps, vinyl-type wallpaper may provide effective and esthestically acceptable cover layers and this aspect is being investigated.

5.3 Cost-Effectiveness Criteria for Radon Daughter Control

The potential health effects from the use of Ra-226-bearing building materials will be due to external gamma radiation exposure and an internal dose mainly due to inhalation of radon daughters. The external doses from walls and floor

Table 15

Comparison of Sealant Effectiveness

	TLD Measurements			Charcoal Measurements	
Coating	No. of runs	Average dose, WL	Percent reduction	No. of runs	Av. Rn-222 Activity, pCi/l
Bare wall	4	0.010	--	4	4.7
Block filler only	5	0.011	0%		
Epoxy paint only	1	0.008	20%	2	2.3
Epoxy + filler	5	0.002	80%	1	2.4
Latex + filler	5	0.005	50%	3	2.9
Surewall	4	0.016	0%		
Plastic sheet 70μ thick	1	0.0003	97%		

slabs will, in general, be less significant than the inhalation dose. It is for this reason that reduction of radon emanation would be considered as a possible control procedure. To determine the cost-effectiveness of such procedures, a monetary criterion must be adopted for any health effects observed. Moeller and Underhill (Mo76) have shown how the cost per man-rem reduction varies by a factor 10 with changes in occupancy rates. The dollar value per man-rem reduction for the lung and internal dose levels involved is somewhat arbitrary at this time, since the Environmental Protection Agency has not adopted any cost-effectiveness inhalation dose criterion. The closest guide is the NRC cost-effectiveness criterion of $1,000 per whole-body man-rem dose reduction.

If it is decided that population doses from radon daughters in building materials are unacceptably high for individuals or responsible for more than a specified person-rem value per area or nation, then two alternative strategies present themselves:

a. Reduction at source.

By identifying the origin of Ra-226-bearing materials components of particularly high radium content, their use in future construction work may be discouraged or prohibited, thus substituting similar material with lower radioactivity content. This can be done at minimum cost, although some compensation of affected quarries or diversion of the products into less hazardous use may be necessary.

b. Coating of wall and floor surfaces.

Application of coatings can only be regarded as remedial action in cases where existing dose levels, due to radon daughters alone, are considered excessive. To be acceptable, the coating must be impermeable to a specified degree, and to some extent self-sealing over long time periods. A partial reduction of radon emanation would not be adequate because there is no guarantee of continued diffusion at the same rates. Exhalation rate suppression needs to be by at least an order of magnitude to be worthwhile. A surface, once coated, must not be penetrated in any manner, for example by pipe runs, fastenings, or picture hooks.

The costs of a surface treatment are both monetary and intangible:

Monetary costs
  Cost of paint or coating, per m^3 or room
  Labor cost per room or building

Intangible costs
  Loss of utility of wall surface
  Possible reduction in attractiveness of finish
  Increase in gamma-ray exposure due to trapping radon daughters
  Possible need for continued monitoring

The benefits of the treatment are entirely due to reduction in population dose from lower airborne radon daughter concentrations.

The increase in gamma-ray exposure rate has been shown to be relatively small, being less than 25 percent except under unusual geometrical conditions (Cu76, Au74). It is proportionately less important in large rooms. The cost of surface treatment also rises in large rooms. As room size and occupancy increase, the ratio of the inhaled dose to the total dose is expected to rise, making radon daughter control more attractive under those conditions.

In that case, a cost-effectiveness criterion can be developed such that the ratio (dose reduction in person-rem)/(coating cost in dollars) must meet a certain cost criterion to be judged cost effective. The NRC guideline figure of $1,000 per person-rem dose reduction will be used here as a cost-effectiveness criterion (NR75), although $200 per person-rem is probably a more realistic figure.

Harley has suggested a dose conversion factor of 4.3 rad/year per working level exposure; the UNSCEAR recommendation for environmental radon exposures is 7.8 rad/yr per WL. Depending on the quality factor assumed for alpha particles, the rad-rem conversion involves a factor of 3-10. Taking the higher values, one obtains an equivalence of 78 person-rem per WL-year. Assuming an average useful life of 30 years for a residential building, this period represents a dose commitment of 2,340 person-rem per WL. The cost-effectiveness criterion then implies that about $2.3 million could be justified per working-level-person (WLP) reduction, a surprisingly high figure in relation to the perceived risk.

For a school with 1,500 students, who occupy it 8 hours per day, with a wall surface area of 80,000 sq ft, a reduction of radon daughters from 0.1 WL to 0.005 WL represents a dose reduction of 23.75 WLP. At $2.3 million per WLP this implies a cost criterion of $23.75 \times 2.3 \times 10^6/80{,}000$ = $680 per ft^2 treated, a high figure that would justify extensive treatment. This is almost independent of the specific sealant used and assumes minor contribution from gamma-rays from radionculides accumulating below the coating layer.

This relationship can be expressed generally as

$$\text{Benefits} = \Delta D \times C_{dc} \times d_{occ} \quad \text{(in dollars)} \tag{16}$$

$$\begin{aligned} \text{Costs} &= \text{application costs (labor + material)} \\ &\quad + \text{increase in gamma dose} \\ &\quad + \text{maintenance and monitoring costs} \\ &= P_{LM} \,.\, f_A \,.\, A + \Delta D_\gamma \, f_{(r)} \, f_A \, d_{occ} + P_M \, \Delta t \end{aligned} \tag{17}$$

where ΔD = dose reduction in rems due to Rn daughter inhalation

$\Delta D_\gamma = A \,.\, C_u \,.\, \varepsilon \,.\, f_D$

A = exposed wall area

C_u = uranium concentration in wall material

ε = emanation rate

f_D = coating reduction factor

C_{dc} = cost effectiveness criterion, in dollars per person-rem reduction or dollars per working-level-person reduction

d_{occ} = average occupancy of room per year

P_{LM} = painting cost per unit area

P_M = maintenance cost per year per area

f_A = wall surface characteristics (porosity, sealability)

ΔD_γ = incremental gamma dose from radon daughters

$f_{(r)}$ = room size factor

Δt = life time of building

Overall one must satisfy

$$\frac{\Delta D_\infty}{(D_\gamma \cdot f_{(r)} + D_\infty)} > 0.1 \tag{18}$$

And

$$\Delta D \times C_{dc} \times d_{occ} \gg P_{LM}\, f_A\, A + \Delta D_\gamma\, f_{(r)} f_A\, d_{occ} + P_M\, \Delta t \tag{19}$$

6. Summary and Conclusions

A review of previous work indicates that gamma radiation exposure rates in houses surveyed throughout the world usually are the same or somewhat higher than outside when concrete, brick, stone, or stucco are the construction materials, and the same as or somewhat less than outside in frame houses where walls and floors are of wood or non-concrete prefabricated materials. Elevated exposure rates are typically between 0 and 6 μR/hr above outside values, corresponding to dose equivalents from 0 to 30 mrem/yr for continuous occupancy. In many cases, the increase can be represented as a fraction of outside values because construction materials are so often indigenous for economic reasons. On the average, living and working within structures in the U.S. has been estimated to reduce the gamma radiation dose equivalent by 3.2 mrem/yr because of the prevalence of houses where walls function more to attenuate outside radiation than as sources of radiation. This effect may have been reversed in the last decade by the practice of constructing most houses with masonry or masonry facing, such that currently an average elevation of 4 mrem/yr may pertain.

Average Rn-222 daughter concentrations in groups of buildings constructed of materials that do not have elevated radionuclide concentrations are between 0.002 and 0.007 WL. Sets of values for specific areas usually range over two orders of magnitude and are represented better by geometric (logarithmic) than arithmetic distributions. The large range reflects the normal fluctuations of Rn-222 concentrations in outside air and possibly of Rn-222 emanation rates from the ground beneath the house, as well as the influence of various ventilation rates in the monitored structures. Good ventilation alone can decrease Rn-222 daughter concentrations by more than an order of magnitude from levels occurring in a tightly closed room.

Significantly elevated gamma-ray exposure rates and WL values have been found in the United States on uranium-mill tailings and phosphate-mineral lands. Actual building materials have been implicated as a source of significant radiation dose elevation only recently, when phosphate slag, a byproduct in the thermal process for producing phosphorus was found to be used to make concrete blocks and poured concrete. Near phosphorus production plants at Soda Springs and Pocatello, Idaho, and Butte and Anaconda, Montana, surveys by state agencies have so far identified somewhat more than 100 houses in each state that show elevated gamma radiation exposure rates and possibly elevated WL values attributed to concrete that contains the slag. Other sites of elevated external exposure readings with structures that may also have high radiation levels await detailed examination. Surveys have just begun near a thermal-process phosphorus plant at Muscle Shoals, Alabama, and surveys near plants in Polk and Pinellas Counties, Florida, are being considered. Elevated external exposure rates in five buildings in the Atlanta area that were observed in this study are attributed to concrete blocks that contain slag from the Muscle Shoals plant. The slag has also been used as coarse aggregate in road beds, railroad beds, and driveways; may have been used as ballast on flat roofs of houses and to construct septic-tank drain fields; and has been tested for producing glass wool insulation. The slag contains elevated levels of Ra-226 that originate in phosphate ores with high U-238 contents. Not all such ores, however, contain these high radionuclide concentrations.

Other byproducts have been found to contain elevated concentrations of terrestrial radionuclides, but significantly elevated exposure rates in U.S. structures due to their use have not been observed. These materials include gypsum from phosphorus production by the wet process, red mud from bauxite treated for aluminum production, slag from steel, copper and manganese production, and ash from coal burning. Natural products used in building construction that may have elevated terrestrial radionuclide levels include some granite, pumice, shale, and sand. Of these, gypsum and alum shales cause significantly elevated radiation exposures in houses in other countries, while radiation exposures from steel slag are slightly elevated. Measured radiation levels from pumice and ash in the U.S. also are only slightly elevated. Use of gypsum from phosphoric acid production is suspected in the U.S., but elevated levels in houses have not been found. That none of these materials has been found to cause significantly elevated doses in structures may only be due to the relatively few measurements so far performed in U.S. structures.

Typical radiation elevations in the houses in Idaho and Montana constructed with concrete that contains phosphate slag with elevated Ra-226 content are approximately 20 μR/hr for gamma radiation and 0.005 WL for Rn-222 daughters in air. Because the surveys are in their early stages, the values are subject to change. In particular, the WL values have not been based on sufficient measurements to provide long-term averages and to define the contribution of Rn-222 daughters from sources other than construction materials. Calculations of Rn-222 concentrations to be expected from the Ra-226 content in concrete suggest that increases in WL values in normally ventilated building air from this source will not reach the established limits. These measured elevated levels in structures are estimated to expose of the order of 1,000 persons in Idaho and Montana.

The most appropriate preventive measure for significantly elevated radiation exposure in houses is prohibiting use of the material or component with elevated radionuclide content. The proposed rules by EPA under the Resources Conservation and Recovery Act will achieve this result for byproduct materials. Among recommended remedial measures to reduce the concentration of Rn-222 daughters in building air, increased ventilation is the most simple and effective if high WL values are due to poor ventilation. Where Rn-222 daughter concentrations must be reduced by an order of magnitude or more and ventilation is either normal or cannot be conveniently increased, application of sealants that are impermeable to radon penetration appears to be cost-effective. Most tested paints and coatings have not been effective radon barriers, but one such impermeable sealant has been found. Effective use of a sealant requires care to avoid any penetration whatsoever as well as periodic renewal. Elevated gamma-ray exposure rates that require remedial action have not been observed for buildings in the U.S.; if found, removal of the responsible material appears to be the most appropriate countermeasure.

In tests of survey methodology, a NaI(Tl) detector was found effective for categorizing construction materials by radiation exposure potential. These categories were confirmed by measuring in the laborabory the concentrations of the U-238 chain, Th-232 chain, and K-40 in the material, and were found to be consistent with external radiation exposure rates observed in homes under construction. Pressurized ion chambers were used in conjunction with the NaI(Tl) survey meter calibrated relative to the PIC to survey sample buildings for external radiation exposure rates, and these detection instruments are recommended for use. The materials responsible for elevated radiation exposure rates in older buildings were readily located with these detectors. Measurements and calculations were combined to apportion the contributions to the radiation exposure rate between the ground outside and construction materials. To determine whether the Ra-226 precursor of Rn-222 was present in building materials at elevated levels relative to the Th-232 chain and K-40, samples were analyzed in the laboratory or in-situ gamma-ray spectroscopy measurements were performed with a portable Ge(Li) detector.

The test survey in the Atlanta area found brick and concrete building materials generally in three categories of exposure rate potential: medium value with the U-238 and Th-232 chains at concentrations of approximately 1.7 pCi/g each and K-40 at approximately 20 pCi/g, which is at the upper end of the indigenous range for the ground; high values that on the average are 50 percent higher for these radionuclides; and low values at approximately one-half of the medium concentrations. The low and high values were found in only about 1 percent each of the samples. The terrestrial radiation background ranged from 2 to 10 μR/hr in Atlanta and its immediate vicinity. This range was observed in ground-level gamma-ray exposure rate measurements, was inferred from analyses of soil samples, and had also been found in an aerial gamma-ray survey. External exposure rate increments in buildings were generally similar to values reported in surveys elsewhere and could be estimated with the available calculational model that related inside to outside exposure rates in terms of material category and location in the structure. Exceptions were encountered for materials with unusually high radionuclide content. Measurements of Rn-222 concentrations in building air gave consistently higher values than predicted from the Ra-226 concentrations in building materials and Rn-222 concentrations in outside air.

Significantly elevated gamma-ray exposure rates were found in five school and commercial buildings. The increased levels were traced to concrete blocks that had been manufactured in the mid-1960's. These were identified as special light-weight blocks that contained phosphate slag shipped to two Atlanta concrete producers from a thermal-process phosphorus plant in northern Alabama from 1962 until 1968. External radiation exposure rates were elevated 20 μR/hr above background at typical locations in these structures, and were higher at the surfaces of walls constructed with these blocks.

Because the phosphate slag supplied by the Alabama plant is a fine aggregate particularly suited for producing light concrete blocks, apparently far more of it was used in building construction than in Idaho and Montana. Based on the tonnage shipped, 11,000 structures of all types may have been built in the Atlanta area from 1962 to 1968, and an additional 68,000 throughout the southeast, until all shipments were halted in December 1978. On the basis of highly speculative estimates of the number of structures, approximately 300,000 persons may be exposed to radiations from this phosphate slag in structures. The few external exposure rates measured in Atlanta and the radionuclide contents of various phosphate slags taken with the fractions of slag used in the concrete product suggest that dose equivalents to persons from this slag are somewhat less than those in Idaho and Montana. Based on measured gamma-ray exposure rates and computed Rn-222 daughter concentrations, typical elevations of 12 μR/hr and 0.003 WL above background are predicted in rooms where the blocks are used for the entire wall but ventilation is normal.

The inference of widespread use of a building material that causes significantly elevated exposure rates in structures needs to be examined further by searching records of slag suppliers, concrete block producers, and builders to delineate concrete block use; surveying those structures identified to contain slag-bearing concrete that would be expected to cause highest radiation doses due to highest Ra-226 concentrations, massive use of slag, poor ventilation, and occupancy factor near unity; and studying in detail the relation between Ra-226 concentrations in the blocks, the geometrical configurations of the blocks, the gamma ray exposure rate, and WL values. The usually encountered external gamma radiation exposure rates and WL values, however, are expected to be consistently below the levels that require remedial action on the basis of the Ra-226 content of the examined blocks and slag.

The review of national surveys in other countries and of studies undertaken in the U.S. suggests that a nationwide survey may be needed to determine population radiation doses due to building material and to identify structures with significantly elevated doses. Concentrations of radionuclides in building materials and factors such as geometrical configurations and ventilation rates are too variable for reliable predictions of population doses based on some local samples or limited studies. Moreover, materials with relatively high radionuclide concentrations would be expected to be used in construction too infrequently to be encountered except in thorough nationwide surveys or by luck.

Experience in these nationwide surveys suggests that such a survey in the U.S. should combine several approaches: mapping the area for patterns of external radiation exposure and Rn-222 daughter concentrations; surveying construction materials for radiation dose potential; categorizing buildings on the basis of the radiation dose potential of materials for selecting sample structures for surveying; surveying gamma-ray exposure rates in a selected sample of houses; analyzing materials in houses with elevated exposure rates to estimate Ra-226 levels; and performing a detailed survey for WL values in the buildings found to contain elevated Ra-226 levels and a brief survey in all others. Although this effort is more complex than simply performing measurements of gamma radiation exposure rates and WL values in selected sample structures, it reduces the possibility of overlooking significantly elevated exposure categories among construction materials and makes feasible a survey of WL values that would otherwise require extraordinary resources.

Surveys can be performed most effectively on a local basis with national coordination. The region of each survey can be a state or a metropolitan area including its surroundings. Federal coordination is needed to provide uniform study protocols, assist in instrument calibration, maintain quality assurance of measurements, and combine and exchange data. A 3-year period is estimated to complete the survey in each area.

The following topics were identified as requiring further consideration in view of the information derived from the reviewed reports and the present studies:

1. Selection of sampling frequency for survey. The German Federal Republic has successfully completed a nationwide survey of gamma-ray exposure rates in homes at a frequency of 1 sample per 2,000 homes, but the published data do not give numerical indications of the extent to which all utilized building materials and their constituents were represented, the uncertainty of mean exposure rates in the various structural categories, and the probability of having missed significantly elevated exposures. It is believed that such values for selecting sample frequencies that correspond to an acceptable level of uncertainty in obtaining mean exposure values and including all structures with elevated exposures could be derived from the unpublished data.

2. Identification of building materials with high radionuclide contents. A survey of structures may miss structures with significantly elevated radiation doses even if the sampling mesh is relatively fine. To reduce the possibility of this occurrence, building material surveys can be undertaken by attempting to examine either all building material constituents or all building materials and then tracing elevated levels to their constituents. This report proposes that the latter procedure be included in the U.S. survey of radiation in structures so that materials can be categorized by their radiation dose potential.

3. Estimation of Rn-222 concentrations in structures. The currently used calculational model appears to underestimate Rn-222 concentrations in structures by a large factor. The model, however, does not include a source term for Rn-222 entering the structure directly from the ground beneath it. Moreover, measurements of Rn-222 concentrations in structures for survey purposes have usually not been accompanied by simultaneous measurements of Rn-222 concentrations in outside air, emanation rates from building material surfaces, or ventilation rates; these important factors in the model are usually based on brief measurements or estimates. A careful study to develop a satisfactory model is recommended to permit determination of the contribution by building materials to the Rn-222 concentration and WL value within a structure.

4. Recognition of sensitivity limits for determining dose elevation due to building material. Both inside and outside measurements of gamma-ray exposure rates and WL values have been found uncertain to an appreciable degree because the background varies among locations, values within structures vary among locations, and all values fluctuate with time.

These uncertainties are magnified in computing differences between inside and outside values, especially if only a fraction of the inside value is attributed to building materials. The probable error can be reduced by performing simultaneous long-term measurements inside and outside, but even then, care must be taken to assure that elevations determined to be of the same magnitude as ambient values exceed their uncertainties, which appear to be of the order of several μR/hr and several milli-WL.

5. Guidance in selecting cost and benefit values to evaluate remedial measures. A value of equivalent cost per person-rem/yr to the lung is needed for cost-benefit calculations. A weighting factor is also needed for evaluating application of the two most highly recommended remedial measures for elevated WL values in structures -- increased ventilation and impermeable barriers -- because both involve the possibility of unanticipated termination and consequent increased exposure to persons.

6. Consideration of the dose from high WL values in normal structures. Many structures have relatively high WL values, if the measurements that indicate geometric means between 0.002 and 0.007 WL and geometric standard deviations near 2 are generally applicable in the U.S. to "normal" structures, i.e., those that do not have significantly elevated radionuclide concentrations in their building materials. A survey to determine mean values and identify structures with significantly elevated values therefore appears desirable, whether or not construction materials are the source of the Rn-222 in building air. This survey would differ from the one described above because major emphasis would be placed on structures in areas with high Ra-226 concentrations in the ground.

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APPENDIX A

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Calculation of Gamma Radiation Exposure Rate in Structures

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1234567890123456789012345678901234567890123456789012345678901234567890123456789

      PROGRAM BOX(TAPE10,OUTPUT,TAPE9,TAPE6=OUTPUT)
      DIMENSION AMU(24),R(24),DOSE(20,20,20),FQ(3),T1(6),TX(6)
      DIMENSION TMU(6),RHO(6),DOSEOLD(20,20,20)
      REAL MMOEI
C     MMOEI IS THE GEORGIA TECH LIBRARY FUNCTION WHICH CALCULATES THE
C     VALUE OF THE EXPONENTIAL INTEGRAL
  604 FORMAT(1H 40X44HDOSE RATE VS POSITION FOR RECTANGULAR VOLUME)
C     SET UP COFFS FOR GAUSS QUADRATURE
      PI=3.14159
      NRUN=1
      AMU(1)=.00921968*.5
      AMU(2)=.04794137*.5
      AMU(3)=.11504866*.5
      AMU(4)=.20634102 *.5
      AMU(5)=.31608425 *.5
      AMU(6)=.43738329 *.5
      R(1)=.02358767 *.5
      R(2)=.05346966 *.5
      R(3)=.08003916 *.5
      R(4)=.10158371 *.5
      R(5)=.11674669 *.5
      R(6)=.12457352 *.5
      DO91 N=7,12
      J=13-N
      AMU(N)=.5-AMU(J)
   91 R(N)=R(J)
      DO92 N=13,24
      J=N-12
      AMU(N)=0.5+AMU(J)
   92 R(N)=R(J)
      WRITE(9,604)
      READ(10,*) (FQ(I),I=1,3),NX,NY,NZ,NTHICK
C     FQ(1)=ROOM LENGTH (IN.)
C     FQ(2)=ROOM WIDTH (IN.)
C     FQ(3)=ROOM HEIGTH (IN.)
C     NX=NUMBER OF MESH POINTS IN THE X-DIRECTION
C     NY=  "     "  "    "     "  "  Y-    "
C     NZ=  "     "  "    "     "  "  Z-    "
C     NZ SHOULD BE AN EVEN NUMBER
C     NTHICK=NUMBER OF PLANAR THICKNESSES INTO WHICH EACH FLOOR OR
C     WALL IS DIVIDED.  THIS RESULTS IN A VOLUME SOURCE BEING AP-
C     PROXIMATED BY A NUMBER(NTHICK) OF PLANAR SOURCES.
  112 READ(10,*)CST,ET,TMUAIR
C     CST=CONSTANT TO CONVERT ENERGY FLUX IN MEV/CM**2-SEC TO
C     ABSORBED DOSE RATE IN RAD/HR PER CURIE/CM**2 .
C     ET=TOTAL GAMMA ENERGY IN MEV/DISINTEGRATION
C     TMUAIR=TOTAL LINEAR ABSORPTION COEFFICIENT OF AIR (1./IN.)
      WRITE(9,10) FQ(1),FQ(2),FQ(3),NTHICK
   10 FORMAT(1X,*LENGTH=*,F8.3,5X,*WIDTH=*,F8.3,5X,*HEIGTH=*,F8.3,
     1 5X,*NTHICK=*,I3//)
      WRITE(9,11) CST,ET,TMUAIR
   11 FORMAT(1X,*CST=*,E12.4,5X,*ET=*,E12.4,5X,*TMUAIR=*,E12.4//)
      DO 3 I=1,6
      READ(10,*)TX(I),TMU(I),RHO(I)
C     I=1 CORRESPONDS TO THE FLOOR
C     I=2       "        "  "  CEILING
C     I=3       "        "  "  RIGHT END WALL
C     I=4       "        "  "  LEFT END WALL
C     I=5       "        "  "  FRONT WALL
C     I=6       "        "  "  BACK WALL
C     TX(I)=THICKNESS(IN.) OF THE FLOOR, CEILING, OR WALL DEPENDING
C     ON THE ABOVE INDEX
C     TMU(I)= SAME AS THE ABOVE EXCEPT TOTAL LINEAR
```

```
C       ABSORPTION COEFFICIENT (1./IN.)
C       RHO(I)= SAME AS THE ABOVE EXCEPT DENSITY (GM./CC)
      3 WRITE(9,12) I,TX(I),TMU(I),RHO(I)
     12 FORMAT (1X,*IW=*,I2,5X,*THICK=*,E10.3,5X,*TMU=*,E10.3,
     1   5X,*RHO=*,E10.3/)
    123 DO 700 I=1,20
        DO 700 J=1,20
        DO 700 K=1,20
        DOSEOLD(I,J,K)=0.0
    700 DOSE(I,J,K)=0.0
        IF(NRUN-2)500,501,502
C       NRUN=1  --. FLOOR CALCULATION ONLY
C       NRUN=2  --  FOUR WALL CALCULATION ONLY
C       NRUN=3  -- FLOOR + FOUR WALL CALCULATION
    500 IWL=IWUP=1
        GO TO 503
    501 IWL=3
        IWUP=6
        GO TO 503
    502 IWL=1
        IWUP=5
    503 DO 1012 IW=IWL,IWUP
        IF(IW.EQ.2) GO TO 1012
        T1(IW)=0.1E-10
        DO 1014 ITK=1,NTHICK
        SMUT=TMU(IW)*T1(IW)
        SCLAD=T1(IW)
        NNX=NX+1
        NNY=NY+1
        NNZ=NZ+1
        DO 1011 K=1,NNZ
        DO 1011 J=1,NNY
        DO 1011 IX=1,NNX
        IF(IW.LE.2) GO TO 50
        IF(IW.LE.4) GO TO 51
        IF(IW.LE.6) GO TO 52
     50 FA=FQ(1)
        FB=FQ(2)
        DX=FQ(1)/(2*NX)
        DY=FQ(2)/(2*NY)
        DZ=FQ(3)/(NZ)
        FX=DX*(IX-1)
        FY=DY*(J-1)
        FZ=DZ*(K-1)
        IF(IW.EQ.2) FZ=DZ*(2*NZ-K+1)
        GO TO 888
     51 FA=FQ(3)
        FB=FQ(2)
        DX=FQ(3)/(NZ)
        DY=FQ(2)/(2*NY)
        DZ=FQ(1)/(2*NX)
        FX=DX*((NZ/2)-K+1)
        FY=DY*(J-1)
        FZ=DZ*(NX-IX+1)
        IF(IW.EQ.4) FZ=DZ*(NX+IX-1)
        GO TO 888
     52 FA=FQ(1)
        FB=FQ(3)
        DX=FQ(1)/(2*NX)
        DY=FQ(3)/(NZ)
        DZ=FQ(2)/(2*NY)
        FX=DX*(IX-1)
        FY=DY*((NZ/2)-K+1)
        FZ=DZ*(NY-J+1)
        IF(IW.EQ.5) FZ=DZ*(NY+J-1)
```

```
  888 SMFP=SMUT+TMUAIR*FZ
      ZDIST=SCLAD+FZ
      BARMU=SMFP/ZDIST
    4 X=ABS(FX)*BARMU
      A=ABS(FA)*BARMU
      B=ABS(FB)*BARMU
      Z=ABS(ZDIST)*BARMU
      Y=ABS(FY)*BARMU
      V=X-.5*A
      VC=Y-.5*B
      IF(V)301,302,301
  302 V=.1E-10
  301 IF(VC)303,304,303
  304 VC=.1E-10
  303 IF(X)5,6,5
    6 IF(Y)7,101,7
    5 U=Y/X-B/A
      IF(U)8,8,7
    7 UX=Y
      UY=X
      UB=A
      UA=B
      X=UX
      Y=UY
      A=UA
      B=UB
      UV=VC
      UVC=V
      V=UV
      VC=UVC
    8 IF(V)101,9,9
    9 IF(VC)102,103,103
C     IN ZONE 1
  101 TH1=-ATAN(-V/(.5*B+Y))
      TH2=ATAN((.5*A+X)/(.5*B+Y))
      TH3=ATAN(-VC/(.5*A+X))+.5*PI
      TH4=ATAN(V/VC)+PI
      PHI=0.0
      EI1= MMDEI(1,-Z,IER)
      Q=-EI1
      DO201 I=1,24
      TH=2.*PI*AMU(I)+TH1
      IF(TH-TH2)211,212,212
  212 IF(TH-TH3)213,214,214
  214 IF(TH-TH4)215,216,216
  211 SX=(Y+.5*B)/COS(TH)
      GO TO 217
  213 SX=(X+.5*A)/SIN(TH)
      GO TO 217
  215 SX=VC/COS(TH)
      GO TO 217
  216 SX=V/SIN(TH)
  217 S=SQRT (SX**2+Z**2)
      EI2= MMDEI(1,-S,IER)
  201 PHI=PHI+R(I)*(Q+EI2)
      PHI=.5*PHI
      GO TO 1010
C     IN ZONE 2
  102 TH1=ATAN(V/(Y+.5*B))
      TH2=ATAN((X+.5*A)/(Y+.5*B))
      TH3=ATAN(-VC/(X+.5*A))+.5*PI
      TH4=ATAN(-VC/V)+.5*PI
      PHI=0.0
      DTH=TH4-TH1
      DO236 I=1,24
```

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```
      TH=TH1+AMU(I)*DTH
      IF(TH-TH2)231,232,232
  232 IF(TH-TH3)233,234,234
  231 SX1=V/SIN(TH)
      SX2=(Y+.5*B)/COS(TH)
      GO TO 235
  233 Q=1./SIN(TH)
      SX1=V*Q
      SX2=(X+.5*A)*Q
      GO TO 235
  234 SX1=V/SIN(TH)
      SX2=VC/COS(TH)
  235 S1=SQRT(SX1**2+Z**2)
      S2=SQRT(SX2**2+Z**2)
      EI3= MMDEI(1,-S1,IER)
      EI4= MMDEI(1,-S2,IER)
  236 PHI=PHI+(-EI3+EI4)*R(I)
      PHI=PHI*DTH/(4.*PI)
      GO TO 1010
C     IN ZONE 3
  103 TH1=ATAN(V/(Y+.5*B))
      TH2=ATAN((X+.5*A)/(Y+.5*B))
      TH3=ATAN((X+.5*A)/VC)
      TH4=ATAN(V/VC)
      PHI=0.0
      DTH=TH3-TH1
      PHI=0.0
      DO226 I=1,24
      TH=TH1+AMU(I)*DTH
      IF(TH-TH2)221,222,222
  221 SX1=V/SIN(TH)
      SX2=(Y+.5*B)/COS(TH)
      GO TO 225
  222 IF(TH-TH4)223,224,224
  223 Q=1./SIN(TH)
      SX1=V*Q
      SX2=(X+.5*A)*Q
      GO TO 225
  224 SX1=VC/COS(TH)
      SX2=(X+.5*A)/SIN(TH)
  225 S1=SQRT(SX1**2+Z**2)
      S2=SQRT(SX2**2+Z**2)
      EI5= MMDEI(1,-S1,IER)
      EI6= MMDEI(1,-S2,IER)
  226 PHI=PHI+(-EI5+EI6)*R(I)
      PHI=PHI*DTH/(4.*PI)
 1010 FX1=DOSEOLD(IX,J,K)
      PATH=T1(IW)*TMU(IW)
      A=22.094
      ALFA1=-0.05859
      ALFA2=-0.00604
      IF(ET.EQ.0.1606) GO TO 1200
      A=30.339
      ALFA1=-0.10115
      ALFA2=-0.05162
      IF(ET.EQ.1.701) GO TO 1200
      A=28.559
      ALFA1=-0.09052
      ALFA2=-0.03939
 1200 BF=A*EXP(-ALFA1*PATH)+(1.-A)*EXP(-ALFA2*PATH)
C     BF= TAYLOR FORM OF THE DOSE RATE BUILDUP FACTOR
      FX2=CST*ET*PHI*RHO(IW)*1.081E+05*BF
      IF(ITK.GT.1)DOSE(IX,J,K)=DOSE(IX,J,K)+(FX1-FX2)/ALOG(FX1/FX2)
     1*TK(IW)/NTHICK
C     DOSE(IX,J,K)= DOSE RATE AT EACH MESH POINT
```

```
C     ALL DOSE RATES ARE IN UNITS OF MICRO-R/HR PER PICO-CURIE/GM.
      DOSEOLD(IX,J,K)=FX2
 1011 CONTINUE
 1014 T1(IW)=T1(IW)+TX(IW)/(NTHICK)
      WRITE(9,13) DX,DY,DZ
   13 FORMAT(1X,*DX=*,F8.3,5X,*DY=*,F8.3,5X,*DZ=*,F8.3//)
 1012 CONTINUE
      DO 110 K=1,NNZ
      WRITE(9,121) K
  110 WRITE(9,120)((DOSE(IX,J,K),IX=1,NNX),J=1,NNY)
  120 FORMAT(7(1X,E12.5))
  121 FORMAT(//45X,*K=*,I5)
C     CALCULATION OF AVERAGE DOSE RATE
      SUM=0.0
      DO 400 I=1,NX
      DO 400 J=1,NY
      DO 400 K=2,NNZ
  400 SUM=SUM+DOSE(I,J,K)
      DOSEAVE=SUM/(NX*NY*NZ)
C     DOSE RATES ON THE FLOOR & WALL SURFACES ARE NOT INCLUDED
C     IN THE AVERAGE DOSE RATE CALCULATION
      WRITE(9,122) DOSEAVE
  122 FORMAT(/1X,*AVERAGE DOSE RATE IN VOLUME=*,E12.5/1H1)
      NRUN=NRUN+1
      IF(NRUN.LE.3) GO TO 123
  124 STOP
      END
```

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```
C-MMDEI----------S-------LIBRARY 3--------------------------------------
C
C   FUNCTION                - COMPUTE SINGLE PRECISION VALUES OF THE
C                               EXPONENTIAL INTEGRALS
C   USAGE                   - FUNCTION MMDEI (IOPT,ARG,IER)
C   PARAMETERS   MMDEI      - OUTPUT VALUE. MMDEI MUST BE TYPED REAL
C                               IN THE CALLING PROGRAM.
C                IOPT       - INPUT OPTION.
C                             FOR IOPT = 1, THE INTEGRAL (FROM -INFINITY TO
C                               ARG) OF EXP(T)/T DT WILL BE EVALUATED IF ARG
C                               IS GREATER THAN 0. IF ARG IS LESS THAN 0.0,
C                               (-1)*THE INTEGRAL (FROM -ARG TO INFINITY)
C                               OF EXP(-T)/T DT WILL BE EVALUATED.
C                             FOR IOPT = 2, THE INTEGRAL (FROM ARG TO
C                               INFINITY) OF EXP(-T)/T DT WILL BE EVALUATED.
C                               ARG MUST BE GREATER THAN 0.
C                             FOR ICPT = 3, EXP(-ARG)*THE INTEGRAL (FROM
C                               -INFINITY TO ARG) OF EXP(T)/T DT WILL BE
C                               EVALUATED IF ARG IS GREATER THAN 0. IF ARG
C                               IS LESS THAN 0.0, EXP(-ARG)*(-1)*THE
C                               INTEGRAL (FROM -ARG TO INFINITY) OF
C                               EXP(-T)/T DT WILL BE EVALUATED.
C                ARG        - INFUT PARAMETER. SEE IOPT DESCRIPTION.
C                IER        - ERROR PARAMETER.
C                             TERMINAL ERROR = 128+N.
C                               N = 1 INDICATES THAT IOPT WAS LESS THAN 1
C                                 OR GREATER THAN 3. MMDEI IS SET TO MACHINE
C                                 INFINITY.
C                               N = 2 INDICATES THAT ARG WAS EQUAL TO 0.0.
C                                 MMDEI IS SET TO MACHINE INFINITY IF IOPT
C                                 = 2 AND NEGATIVE MACHINE INFINITY IF IOPT
C                                 = 1 CR 3.
C                               N = 3 INDICATES THAT AN OVERFLOW WOULD HAVE
C                                 OCCURRED. IF IOPT = 1, MMDEI IS SET TO
C                                 MACHINE INFINITY.
C                               N = 4 INDICATES THAT AN UNDERFLOW WOULD
C                                 HAVE OCCURRED. MMDEI IS SET TO 0.0 IF
C                                 IOPT = 1 OR 2.
C                             WARNING WITH FIX = 64+N.
C                               N = 5 INDICATES THAT ARG WAS NEGATIVE FOR
C                                 IOPT = 2. CALCULATION CONTINUES USING
C                                 ABS(ARG).
C   PRECISION               - SINGLE
C   REQD. IMSL RCUTINES     - UERTST
C   LANGUAGE                - FORTRAN
C-----------------------------------------------------------------------
```